

11/05/99
JCSB U.S. PTO

UTILITY PATENT APPLICATION TRANSMITTAL

(New Nonprovisional Applications Under 37 CFR § 1.53(b))

Attorney Docket No.

CISCP601C2

A

TO THE ASSISTANT COMMISSIONER FOR PATENTS:

Transmitted herewith is the patent application of () application identifier or (X) first named inventor, Gregory G. Raleigh, entitled SPATIO-TEMPORAL PROCESSING FOR INTERFERENCE HANDLING (AS AMENDED), for a(n):

() Original Patent Application.

(X) Continuing Application (prior application not abandoned):

(X) Continuation () Divisional () Continuation-in-part (CIP)
of prior Application No. 08/921,633, filed 8/27/1997.

(X) Please add after the title of the application "This is a

(X) Continuation () Divisional () Continuation-in-part (CIP)
of Application No. 08/921,633, filed 8/27/1997, which is hereby incorporated by reference."

(X) Please add after the title of the application "This application claims the benefit of U.S. Provisional Application

No. 60/025,277, filed 8/29/1996, and U.S. Provisional Application No. 60/025,228, filed 8/29/1996, which are hereby incorporated by reference."

Enclosed are:

(X) Specification; 71 Total Pages.

(X) Drawing(s); 26 Total Sheets.

(X) Oath or Declaration:

() A Newly Executed Combined Declaration and Power of Attorney:

() Signed.

() Unsigned.

() Partially Signed.

(X) A Copy from a Prior Application for Continuation/Divisional (37 CFR § 1.63(d)).

() Signed Statement Deleting Inventor(s) Named in the Prior Application. (37 CFR § 163(d)(2)).

() Power of Attorney.

(X) Return Receipt Postcard.

() Associate Power of Attorney.

(X) A Check in the amount of \$1,870.00 for the Filing Fee.

(X) Preliminary Amendment.

() Information Disclosure Statement and Form PTO-1449.

() A Duplicate Copy of this Form for Processing Fee Against Deposit Account.

() A Certified Copy of Priority Documents (if foreign priority is claimed).

() Statement(s) of Status as a Small Entity.

() Statement(s) of Status as a Small Entity Filed in Prior Application, Status Still Proper and Desired.

() Other: _____

CLAIMS AS FILED

| FOR | NO. FILED | NO. EXTRA | RATE | FEE |
|---|-----------|-----------|---------|-------------|
| Total Claims | 21 | 1 | \$18.00 | \$ 18.00 |
| Independent Claims | 17 | 14 | \$78.00 | \$ 1,092.00 |
| Multiple Dependent Claims (if applicable) | | | | \$0.00 |
| Assignment Recording Fee | | | | \$0.00 |
| Basic Filing Fee | | | | \$760.00 |
| Total Filing Fee | | | | \$ 1,870.00 |

At any time during the pendency of this application, please charge any fees required or credit any overpayment to Deposit Account No. 50-0685 (Order No. CISCP601C2).

Respectfully submitted,

By: _____

Dan H. Lang, Reg. No. 38,531

Date: November 5, 1999

Correspondence Address:

Customer No. 21912

RITTER, VAN PELT & YI LLP

4906 El Camino Real, Suite 205

Los Altos, CA 94022

Phone: 650-903-3500

Fax: 650-903-3501

I hereby certify that this is being deposited with the U.S. Postal Service "Express Mail Post Office to Addressee" service under 37 CFR § 1.10 on the date indicated below and is addressed to:

Assistant Commissioner for Patents
Box Patent Application
Washington, D.C. 20231

By: _____

Typed Name: Jack Limper

Express Mail Label No.: EL422309695US

Date of Deposit: November 5, 1999

PATENT
IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

| | | |
|--|---|----------------------|
| In re the application of: RALEIGH et al. |) | Examiner: Unassigned |
| |) | |
| Application No. Unassigned |) | Art Unit: Unassigned |
| |) | |
| Filed: Herewith |) | |
| |) | November 5, 1999 |
| For: SPATIO-TEMPORAL PROCESSING FOR |) | |
| INTERFERENCE HANDLING (AS AMENDED) |) | |
| _____ | | |

CERTIFICATE OF MAILING

I hereby certify that this correspondence is being deposited with the United States Postal Service as First Class Mail in an envelope addressed to: Assistant Commissioner of Patents, Washington, DC 20231 on November 5, 1999.

Signed: 
Jodie M. Price

PRELIMINARY AMENDMENT

Assistant Commissioner for Patents
Washington, D.C. 20231

Dear Sir:

Prior to examination, please amend the above-identified application as follows:

IN THE TITLE:

Please change the title to read:

--SPATIO-TEMPORAL PROCESSING FOR INTERFERENCE HANDLING--

IN THE CLAIMS:

Please cancel claims 1-223 and add new claims 224-244 as follows:

224. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel,
said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein each input bin has at least one associated spatial direction; and

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure; and wherein

said weightings are chosen to minimize interference to unintended receivers.

225. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein each input bin has at least one associated spatial direction; and

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure; and wherein

said weightings are chosen based on characterization of an undesired signal subspace and a desired signal subspace.

226. (NEW) The transmitter system of claim 225 wherein said characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of time and frequency.

227. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein there are at least two spatial directions; and

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure and wherein said at least two spatial directions are the same for all of said input bins.

228. (NEW) The transmitter system of claim 227 further comprising:

a system input that receives a group of input symbols wherein each input symbol corresponds to a particular input bin of said time domain substantially orthogonalizing procedure and a particular one of said at least two spatial directions; and wherein

said at least one processing element applies said time domain substantially orthogonalizing procedure to said group of input symbols independently to symbols corresponding to each of said at least two spatial directions; and wherein

said spatial processor, for each independent application of said time domain substantially orthogonalizing procedure, applies one of said weightings to output of said time domain substantially orthogonalizing procedure, each of said weightings being defined by the particular spatial direction associated with each application of said time domain orthogonalizing procedure and being the same for each output bin of said time domain substantially orthogonalizing procedure.

229. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein there are at least two spatial directions;

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to define contributions to each of said channel inputs; and

wherein said at least one processing element independently applies said substantially orthogonalizing procedure to output of said spatial processor independently for each of said channel inputs;

an encoder that applies a coding procedure to inputs to said spatial processor; and

wherein said coding procedure is applied independently for each of said input bins.

230. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein there are at least two spatial directions;

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to define contributions to each of said channel inputs; and

wherein said at least one processing element independently applies said substantially orthogonalizing procedure to output of said spatial processor independently for each of said channel inputs;

an encoder that applies a coding procedure to inputs to said spatial processor; and

wherein said coding procedure is applied independently for each of said spatial directions.

231. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein there are at least two spatial directions;

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to define contributions to each of said channel inputs; and

wherein said at least one processing element independently applies said substantially orthogonalizing procedure to output of said spatial processor independently for each of said channel inputs;

an encoder that applies a coding procedure to inputs to said spatial processor; and

wherein said coding procedure is applied independently for each of said subchannels.

232. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein there are at least two spatial directions;

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to define contributions to each of said channel inputs; and

wherein said at least one processing element independently applies said substantially orthogonalizing procedure to output of said spatial processor independently for each of said channel inputs;

an encoder that applies a coding procedure to inputs to said spatial processor; and

wherein said coding procedure is applied independently for each of said subchannels.

233. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein there are at least two spatial directions;

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to define contributions to each of said channel inputs; and

wherein said at least one processing element independently applies said substantially orthogonalizing procedure to output of said spatial processor independently for each of said channel inputs;

an encoder that applies a coding procedure to inputs to said spatial processor; and

wherein said coding procedure comprises a turbo coding procedure.

234. (NEW) A transmitter system for transmitting via a plurality of inputs to a channel, said transmitter system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into input bins;

a spatial processor employing weightings among said channel inputs to define spatial directions wherein there are at least two spatial directions;

wherein said transmitter system transmits information in subchannels of said channel, each of said subchannels being defined by a combination of input bin and spatial direction, by employing said at least one processing element for at least two independent applications of said time domain substantially orthogonalizing procedure;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to define contributions to each of said channel inputs; and

wherein said at least one processing element independently applies said substantially orthogonalizing procedure to output of said spatial processor independently for each of said channel inputs;

an encoder that applies a coding procedure to inputs to said spatial processor; and

wherein said coding procedure belongs to a group consisting of:

convolutional coding, Reed-Solomon coding, CRC coding, block coding, and interleaving.

235. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

and wherein said weightings are chosen to minimize interference from undesired transmitters.

236. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

and wherein said weightings are chosen based on characterization of a desired signal subspace and an undesired signal subspace.

237. (NEW) The transmitter system of claim 236 wherein said characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of time and frequency.

238. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

and wherein said at least two spatial directions are the same for all of said output bins.

239. (NEW) The transmitter system of claim 238 further comprising:

a system input that receives input time domain symbols via said channel outputs;

wherein said at least one processing element applies said time domain substantially orthogonalizing procedure to said input symbols independently for each of said at least two spatial directions; and

wherein said spatial processor, applies ones of said weightings to said input time domain symbols to develop input to said independent applications of said time domain substantially orthogonalizing procedure, each of said weightings being defined by a corresponding one of said at least two spatial directions, and being the same for each input bin of said time domain substantially orthogonalizing procedure.

240. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

wherein said at least one processing element applies said substantially orthogonalizing procedure independently for each of said channel outputs;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to output of said at least one processing element to define contributions from each of said channel outputs; and

a decoder that applies a decoding procedure to outputs from said spatial processor; and

wherein said decoding procedure is applied independently for each of said spatial directions.

241. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

wherein said at least one processing element applies said substantially orthogonalizing procedure independently for each of said channel outputs;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to output of said at least one processing element to define contributions from each of said channel outputs; and

a decoder that applies a decoding procedure to outputs from said spatial processor; and

wherein said decoding procedure is applied independently for each of said output bins.

242. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

wherein said at least one processing element applies said substantially orthogonalizing procedure independently for each of said channel outputs;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to output of said at least one processing element to define contributions from each of said channel outputs; and

a decoder that applies a decoding procedure to outputs from said spatial processor; and

wherein said decoding procedure is applied independently for each of said subchannels.

243. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

wherein said at least one processing element applies said substantially orthogonalizing procedure independently for each of said channel outputs;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to output of said at least one processing element to define contributions from each of said channel outputs; and

a decoder that applies a decoding procedure to outputs from said spatial processor; and

wherein said decoding procedure is based on one of:

convolutional coding, trellis coding, Reed-Solomon coding, CRC coding, block coding, and interleaving.

244. (NEW) A receiver system for receiving via a plurality of outputs from a channel, said receiver system comprising:

at least one processing element that applies a time domain substantially orthogonalizing procedure to divide said channel into output bins;

a spatial processor employing weightings among said channel outputs to define spatial directions wherein each output bin has at least one associated spatial direction; and

wherein said receiver system receives information via subchannels of said channel, by employing at least two independent parallel applications of said substantially orthogonalizing procedure by said at least one processing element, each of said subchannels being defined by a combination of output bin and spatial direction;

wherein said at least one processing element applies said substantially orthogonalizing procedure independently for each of said channel outputs;

wherein said spatial processor, for each of said spatial directions applies one of said weightings to output of said at least one processing element to define contributions from each of said channel outputs;

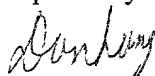
a decoder that applies a decoding procedure to outputs from said spatial processor; and

wherein said decoding procedure is based on turbo coding.--

CONCLUSION

Consideration of the application and allowance of all claims are respectfully requested. If at any time the Examiner believes that a telephone conference would be helpful in expediting this matter, please contact the undersigned at (650) 903-3507.

Respectfully submitted,



Dan H. Lang

Registration No. 38,531

RITTER, VAN PELT & YI LLP
4906 El Camino Real, Suite 205
Los Altos, CA 94022
(650) 903-3500

PATENT APPLICATION

**SPATIO-TEMPORAL PROCESSING FOR
COMMUNICATION**

Inventors:

GREGORY G. RALEIGH, a citizen
of the United States residing at
539 San Juan Ave.
P.O. Box 1870
El Granada, CA 94018

VINCENT K. JONES, a citizen of the
United States residing at
2208 Hastings Shore Lane
Redwood Shores, CA 94065

MICHAEL A. POLLOCK, a citizen of the
United States residing at
20196 Northbrook Square
Cupertino, CA 95014

Assignee:

CLARITY WIRELESS, INC.
1070 Sixth Avenue
Suite 108
Belmont, CA 94002
a California corporation

Entity: Large

TOWNSEND and TOWNSEND and CREW, LLP
Two Embarcadero Center, 8th Floor
San Francisco, California 94111-3834
(650) 326-2400 tel
(650) 326-2422 fax
dhlang@townsend.com

SPATIO-TEMPORAL PROCESSING FOR COMMUNICATION

STATEMENT OF RELATED APPLICATIONS

The present application claims priority from two provisional applications:

SPATIO-TEMPORAL CODING FOR WIRELESS COMMUNICATION, U.S. Prov. App.

No. 60/025,227 and SPATIO-TEMPORAL CODING TECHNIQUES FOR RAPIDLY

10 FADING WIRELESS CHANNELS, U.S. Prov. App. No. 60/025,228, both filed on August 29, 1996. The contents of both provisional applications are herein incorporated by reference for all purposes.

BACKGROUND OF THE INVENTION

15 The present invention relates to digital communication and more particularly to a space-time communication system.

The ability to communicate through wireless media is made difficult by the inherent characteristics of how transmitted signals propagate through the environment. A communication signal transmitted through a transmitter antenna element travels along
20 multiple paths to the receiving antenna element. Depending on many factors including the signal frequency and the terrain, the paths along which the signal travels will exhibit different attenuation and propagation delays. This results in a communication channel which exhibits fading and delay spread.

It is well known that adaptive spatial processing using multiple antenna arrays
25 increases the communications quality of wireless systems. Adaptive array processing is known to improve bit error rate, data rate, or spectral efficiency in a wireless communication system. The prior art provides for methods involving some form of space-time signal processing at either the input to the channel, the output to the channel, or both. The space-time processing step is typically accomplished using an equalization structure wherein the
30 time domain equalizer tap settings for a multitude of antennas are simultaneously optimized. This so-called "space-time equalizaion" leads to high signal processing complexity if the delay spread of the equivalent digital channel is substantial.

There is prior art teaching the use of conventional antenna beams or
35 polarizations to create two or more spatially isolated communication channels between a transmitter and a receiver, but only under certain favorable conditions. The radiation pattern cross talk between different physical transmit and receive antenna pairs must provide sufficient spatial isolation to create two or more substantially independent communication channels. This can lead to stringent manufacturing and performance requirements on the physical antenna arrays as well as the receiver and transmitter electronics. In addition, when
40 large objects in the wireless propagation channel cause multipath reflections, the spatial isolation provided by the prior art between any two spatial subchannels can be severely degraded, thus reducing communication quality.

What is needed is a system for more effectively taking advantage of multiple transmitter antennas and/or multiple receiver antennas to ameliorate the deleterious effects of the inherent characteristics of wireless media.

5 SUMMARY OF THE INVENTION

The present invention provides a space-time signal processing system with advantageously reduced complexity. The system may take advantage of multiple transmitter antenna elements and/or multiple receiver antenna elements, or multiple polarizations of a single transmitter antenna element and/or single receiver antenna element. The system is not
10 restricted to wireless contexts and may exploit any channel having multiple inputs or multiple outputs and certain other characteristics. In certain embodiments, multi-path effects in a transmission medium cause a multiplicative increase in capacity.

One wireless embodiment operates with an efficient combination of a substantially orthogonalizing procedure (SOP) in conjunction with a plurality of transmitter
15 antenna elements with one receiver antenna element, or a plurality of receiver antenna elements with one transmit antenna element, or a plurality of both transmitter and receiver antenna elements. The SOP decomposes the time domain space-time communication channel that may have inter symbol interference (ISI) into a set of parallel, space-frequency, SOP bins wherein the ISI is substantially reduced and the signal received at a receiver in one bin of the
20 SOP is substantially independent of the signal received in any other bin of the SOP. A major benefit achieved thereby is that the decomposition of the ISI-rich space time channel into substantially independent SOP bins makes it computationally efficient to implement various advantageous spatial processing techniques embodied herein. The efficiency benefit is due to the fact that the total signal processing complexity required to optimize performance in all of
25 the SOP bins is often significantly lower than the processing complexity required to jointly optimize multiple time domain equalizers.

Another benefit is that in many types of wireless channels where the rank of the matrix channel that exist between the transmitter and the receiver within each SOP bin is greater than one, the combination of an SOP with spatial processing can be used to efficiently
30 provide multiple data communication subchannels within each SOP bin. This has the desirable effect of essentially multiplying the spectral data efficiency of the wireless system. A further feature is the use of spatial processing techniques within each transmitter SOP bin to reduce radiated interference to unintentional receivers. A still further feature is the ability to perform spatial processing within each receiver SOP bin to reduce the deleterious effects of
35 interference from unintentional transmitters.

One advantageous specific embodiment for the SOP is to transmit with IFFT basis functions and receive with FFT basis functions. This particular SOP is commonly referred to as discrete orthogonal frequency division multiplexing (OFDM), and each SOP bin is thus associated with a frequency bin. This embodiment enhances OFDM with the addition
40 of efficient spatial processing techniques.

According to the present invention, space-frequency processing may adaptively create substantially independent spatial subchannels within each SOP bin even in the presence of significant cross talk interference between two or more physical transmit and receive antenna pairs. A further advantage is that the space-frequency processing can
45 advantageously adapt to cross talk interference between the physical antenna pairs even if this cross-talk is frequency dependent, or time varying, or both. Thus, the present invention may provide two or more substantially independent communication channels even in the presence of severe multipath and relatively poor physical antenna radiation pattern performance.

A further understanding of the nature and advantages of the inventions herein may be realized by reference to the remaining portions of the specification and the attached drawings.

100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 depicts a transmitter system according to one embodiment of the present invention.

Fig. 2 depicts a particular substantial orthogonalizing procedure (SOP) useful in one embodiment of the present invention.

Fig. 3 depicts a receiver system according to one embodiment of the present invention.

Fig. 4 depicts a first communication scenario where multipath is found.

Fig. 5 depicts a second communication scenario where multipath is found.

Fig. 6 depicts a third communication scenario where multipath is found.

Fig. 7 depicts a multiple-input, multiple-output (MIMO) channel with interference.

Fig. 8 depicts the use of an SOP in a single-input single-output (SISO) channel.

Fig. 9 depicts the use of an SOP in a MIMO channel according to one embodiment of the present invention.

Fig. 10 depicts the operation of an SOP in the context of one embodiment of the present invention.

Fig. 11 depicts the application of spatial processing to a particular SOP bin at the transmitter end according to one embodiment of the present invention.

Fig. 12 depicts the application of spatial processing to a particular SOP bin at the receiver end according to one embodiment of the present invention.

Fig. 13 depicts the application of spatial processing to N SOP bins at the transmitter end according to one embodiment of the present invention.

Fig. 14 depicts the application of spatial processing to N SOP bins at the receiver end according to one embodiment of the present invention.

Fig. 15 depicts the use of a single spatial direction at the transmitter end for each bin of an SOP according to one embodiment of the present invention.

Fig. 16 depicts the use of a single spatial direction at the receiver end for each bin of an SOP according to one embodiment of the present invention.

Fig. 17 depicts the use of one or more common spatial weighting vectors for all SOP bins at the transmitter end according to one embodiment of the present invention.

Fig. 18 depicts the use of one or more common spatial weighting vectors for all SOP bins at the receiver end according to one embodiment of the present invention.

Fig. 19 depicts the use of an encoder for each SOP bin according to one embodiment of the present invention.

Fig. 20 depicts the use of an encoder for each spatial direction according to one embodiment of the present invention.

Fig. 21 depicts the use of an encoder for each space/frequency subchannel according to one embodiment of the present invention.

Fig. 22 depicts distribution of encoder output over all space/frequency subchannels according to one embodiment of the present invention.

Fig. 23 depicts a detailed diagram of an encoder/interleaver system according to one embodiment of the present invention.

Fig. 24 depicts a transmitter system wherein multiple space/frequency subchannels are employed without spatial orthogonalization according to one embodiment of the present invention.

Fig. 25 depicts a receiver system wherein multiple space/frequency subchannels are employed without spatial orthogonalization according to one embodiment of the present invention.

Fig. 26 depicts an exemplary technique for bit loading with a trellis coder that uses a one-dimensional QAM symbol constellation.

DESCRIPTION OF SPECIFIC EMBODIMENTS

Definitions

A “channel” refers to the input symbol to output symbol relationship for a communication system. A “vector channel” refers to a channel with a single input and multiple outputs (SIMO), or multiple inputs and a single output (MISO). Each h_j entry in the vector channel \mathbf{h} describes one of the complex path gains present in the channel. A “matrix channel” refers to a channel with multiple inputs and multiple outputs (MIMO). Each entry H_{ij} in the matrix \mathbf{H} describes the complex path gain from input j to output i . A “space time channel” refers to the input to output relationship of a MIMO matrix channel, or a SIMO or MISO vector channel, that occurs when multipath signal propagation is present so that the channel contains delay elements that produce inter-symbol interference (ISI) as explained below.

A “spatial direction” is a one dimensional subspace within a matrix or vector communication channel. Spatial directions need not be orthogonal. A spatial direction is typically characterized by a complex input vector and a complex output vector used to weight transmitted or received signals as explained herein.

A “sub-channel” is a combination of a bin in a substantially orthogonalizing procedure (SOP) as explained below and a spatial direction within that bin. A group of spatial subchannels within an SOP bin may or may not be orthogonal.

An “orthogonal dimension” is one member in a set of substantially orthogonal spatial directions.

A channel “subspace” is a characterization of the complex m -space direction occupied by one or more m -dimensional vectors. The subspace characterization can be based on the instantaneous or average behavior of the vectors. A subspace is often characterized by a vector-subspace of a covariance matrix. The covariance matrix is typically a time or frequency averaged outer product of a matrix or vector quantity. The covariance matrix characterizes a collection of average channel directions and the associated average strength for each direction.

A “two norm” metric for a vector is the sum of the squared absolute values for the elements of the vector.

A “Euclidean metric” is a two norm metric.

“Intersymbol interference” (ISI) refers to the self interference that occurs between the delayed and scaled versions of one time domain symbol and subsequent symbols received at the output of a delay spread communication channel. The channel delay spread is caused by the difference in propagation delay between the various multipath components combined with the time domain response of the RF and digital filter elements.

A “substantially orthogonalizing procedure” (SOP) is a procedure that plays a part in transforming a time domain sequence into a parallel set of substantially orthogonal bins, wherein the signals in one bin do not substantially interfere with the signals from other bins. Typically, the transformation from a time domain sequence to a set of substantially

orthogonal bins requires a transmitter SOP with a set of input bins, and a receiver SOP with a set of output bins.

“Convolutional bit mapped QAM” (CBM-QAM) is the coding system that results when the output of a convolutional encoder are grouped and mapped to QAM constellation points.

Fading “structure” occurs when the fading behavior of one or more entries in a channel matrix within an SOP bin is correlated across time, or frequency, or both. This structure can be exploited using advantageously designed estimation filters to improve channel estimation accuracy given multiple frequency samples of the channel matrix entries, or multiple time samples, or both.

A “maximum likelihood sequence detector” is a sequence estimator that computes the most likely transmitted code sequence, from a set of possible sequences, by minimizing a maximum likelihood cost function.

An “antenna element” is a physical radiator used to transmit or receive radio frequency signals. An antenna element does not involve any electronics processing components. A single radiator with two polarization feeds is viewed as two antenna elements.

An “antenna array” is a collection of antenna elements.

A “burst” is a group of transmitted or received communication symbols.

Background Material

The disclosure herein assumes a background in digital communication and linear algebra. The following references are incorporated herein by reference.

Wozencraft & Jacobs, Principles of Communication Engineering (1965).

Haykin, Adaptive Filter Theory, 2nd Ed. (1991).

Strang, Linear Algebra, 3rd Ed. (1988).

Jakes, Microwave Mobile Communication (1974).

Proakis, Digital Communications (1995).

Transmitter Overview

Fig. 1 depicts a transmitter system in accordance with one embodiment of the present invention. Typically an information signal input 2 includes a digital bit sequence, although other forms of digital data or analog data are possible. In the case of digital data, the input data sequence is first fed into an Encoder and Interleaving apparatus 10 where the data is encoded into a symbol stream. The symbol stream is typically a sequence of complex digitized values that represent members of a finite set. Each symbol can be a one dimensional value, or a multidimensional value. An exemplary one dimensional symbol set is a PAM constellation. Note that in this discussion, it is understood that a symbol with in-phase and quadrature components, is considered to be a complex one dimensional symbol, so that the QAM constellation is also viewed as a set of one dimensional symbols. An example multidimensional symbol set is a sequential grouping of QAM constellation members.

The purpose of the encoding process is to improve the bit error rate of the transmitted signal by introducing some form of information redundancy into the transmitted data stream. Useful encoding techniques can involve combinations of a number of well known techniques such as convolutional encoding with bit mapping to symbols, trellis encoding, block coding such as cyclic redundancy check or Reed Solomon coding with bit mapping or Automatic Repeat Queing. An interleaver is often advantageous for distributing the transmitted information among the various subchannels available for transmission. This interleaving distributes the effects of channel fading and interference so that long sequences of symbols

with poor quality are not grouped closely together in the SOP bin sequence that is fed into the receiver decoder. In many applications, it is advantageous to perform a power and bit-loading optimization wherein the number of bits that are mapped to a given encoder symbol, and the signal power assigned to that symbol, are determined based upon the measured communication quality of the space-frequency information subchannel that carries the symbol stream.

After the digital data is encoded into a sequence of symbols, a Training Symbol Injection block 20 may be used to place a set of known training symbol values in the transmitter symbol stream. The purpose of the training symbols is to provide a known input within a portion of the transmitted symbol stream so that a receiver may estimate the communication channel parameters. The channel estimate is used to aid in demodulation and decoding of the data sequence. The training symbols may be injected periodically in time, periodically in frequency, or both. It will be obvious to one skilled in the art that blind adaptive spatial processing techniques can be utilized within each SOP bin at the receiver as an alternative to training with known symbols. In such blind detection implementations, Training Symbol Injection block 20 is unnecessary.

The data plus training symbol stream is then fed into a Transmitter Space-Frequency Pre-Processor (TSFP) block 30. The TSFP block 30 performs two sets of advantageous processing steps on the symbol stream before transmission. One processing step accomplished within the TSFP is the transmitter portion of a substantially orthogonalizing procedure (SOP). When the transmitter portion of the SOP is combined with the receiver portion of the SOP, a set of parallel bins are created in such a manner that information transmitted within one bin does not substantially interfere with information transmitted from another bin after the receive portion of the SOP is completed. One preferred SOP pair is the inverse fast Fourier transform (IFFT) at the transmitter combined with the FFT at the receiver. Another advantageous SOP pair embodiment is a bank of multiple filter and frequency converter pairs (multi-band SOP) with one filter bank located at the transmitter and one filter bank located at the receiver as depicted in Fig. 2. Several other example SOPs including the Hilbert transform pair and generalized wavelet transform pairs will be obvious to one skilled in the art. The other processing step accomplished in the TSFP is spatial processing. The spatial processing step typically multiplies one or more symbols that are destined for transmission in a given SOP bin with one or more spatial vector weights. For convenience in the following discussion, the collection of spatial processing weights applied to the signals transmitted or received in a given SOP bin are sometimes referred to as a matrix. The spatial vector weights are optimized to obtain various desirable performance enhancements.

Fig. 2 depicts a digital baseband filter bank at the receiver and a filter bank located at the transmitter. Each filter of the transmitter filter bank includes a mixer (frequency converter) 60, a bandpass filter 70 and an interpolator 80. Each filter of the receiver filter bank includes a bandpass filter 90, a mixer 60, and a decimator 100.

One transmitter embodiment optimizes the transmitter spatial vector weights so that the multiple subchannels in a given SOP bin can be converted at the receiver into substantially independent received spatial subchannels wherein symbols from one subchannel do not substantially interfere with symbols from another subchannel. Another embodiment optimizes the transmitter spatial vector weight to improve the received power of one or more spatial subchannels within each SOP bin, or to improve the average power of several spatial subchannels within several SOP bins. A further embodiment optimizes the transmitter spatial vector weights within each SOP bin to simultaneously increase the power delivered to the desired receiver within one or more spatial subchannels while reducing interference radiated

to unintended receivers. A yet further embodiment spatial processes one or more symbols within each SOP bin by multiplying each symbol with a transmitter weight vector that is fixed for all SOP bins, with the weight vectors optimized to increase the time or frequency average power delivered to one or more desired receiver spatial subchannels, and possibly reduce the time or frequency averaged interference radiated to unintended receivers. This last embodiment is particularly useful in FDD systems where multipath fading makes it impossible to estimate the forward channel from reverse channel data, but where the average forward channel subspaces are substantially similar to the average reverse channel subspaces. Another embodiment teaches simply routing each symbol from the encoder to one antenna element in each SOP bin without any weighting. Other useful embodiments are discussed herein, and many others useful combinations of spatial processing with an SOP will become obvious to one skilled in the art. It is understood that one or more digital filters are typically used in TSFP 30 to shape the transmitted RF signal spectrum.

Once the encoder symbol sequence is processed by TSFP 30, the processed symbol sequence includes a parallel set of digital time domain signal sequences. Each of these time domain signal sequences is fed into one input of a Modulation and RF System block 40. Modulation and RF System block 40 includes a set of independent RF upconverter chains that frequency convert the digital baseband signal sequence up to the RF carrier frequency. This is accomplished using apparatus that includes digital to analog converters, RF mixer apparatus, and frequency synthesizer apparatus. The details of these elements of the invention are well known and will not be discussed here.

The final step in the transmission process is to radiate the transmitted signal using a Transmit Antenna Array 50. The antenna arrays can be constructed from one or more co-polarized radiating elements or there may be multiple polarizations. If there is multipath signal propagation present in the radio link, or if there are multiple polarizations in the antenna arrays, or if at least one of the antenna elements on one side of the link are in a disparate location from the other elements on the same side of the link, then the invention has the advantageous ability to create more than one subchannel within each SOP bin. It is understood that one physical antenna reflector with a feed that has two polarizations is considered as two antenna elements in all that follows. There are no restrictions on the antenna array geometry or the geometry of each radiating element. A transmitter system invention may adapt to provide optimized performance for any arbitrary antenna array.

Receiver Overview

Fig. 3 depicts a receiver system according to one embodiment of the present invention. The RF signals from each of the elements of an Antenna Array 110 are downconverted to digital baseband using a Demodulation and RF System 120. Demodulation and RF System 120 includes the RF signal processing apparatus to downconvert the RF carrier signal to a baseband IF where it is then digitized. After the digitizer, a timing and frequency synchronization apparatus is used to recover the timing of the transmitted digital signal sequence. Several known techniques may be used for the purpose of synchronization and these techniques will not be discussed herein.

In certain embodiments of the invention, after Demodulation and RF System 120, the digital baseband signal is then fed into a Channel ID block 130 and a Receiver Space-Frequency Processor (RSFP) block 140. Within Channel ID block 130, the characteristics of the digital communication channel are estimated. The estimated channel values consist of entries in a matrix for each SOP bin. The matrix contains complex values representing the magnitude of the spatial channel within the SOP bin from one transmit antenna element to one

receive antenna element. The matrix channel estimate for each SOP bin is provided to RSFP block 140 and Decoder and Deinterleaving block 150.

Some embodiments of the invention involve improving channel estimation performance by exploiting the structured nature of the frequency domain fading that exists in the matrix channels across SOP bins, exploiting the structure in time domain fading of the matrix channels, or exploiting both the frequency and time domain fading structure that is present. By exploiting the frequency domain fading correlation, the entire set of matrix channels within the SOP bins may be estimated even when training information is transmitted in a subset of the SOP bins. This allows for simultaneous transmission of training and data thus reducing overhead. By exploiting the time domain correlation of the channel fading within each SOP bin, channel estimation accuracy is increased for a given time epoch between training events. This reduces the required frequency of training symbol transmission and thus further reduces training overhead. It is understood that it is also possible to separately exploit time domain and frequency domain correlation, with the most beneficial results occurring if both correlation dimensions are used advantageously. It is to be understood that Channel ID block 130 is shown as a separate function even though it may share some elements with RSFP block 140 or Decoder and Deinterleaver block 150.

RSFP block 140 performs the receiver signal processing that is the dual of the two sets of operations performed in TSFP 30. One of the steps performed in RSFP 140 is the receiver half of the SOP. As discussed above, the receiver half of the SOP completes the transformation between the time domain channel with ISI to the substantially orthogonal set of bins. The second set of signal processing operations that can be performed in the RSFP is spatial processing. In one class of embodiments, the receiver spatial processing step combines the output of the SOP bins using one or more vector weighted inner product steps to form one or more one-dimensional received spatial subchannels within each SOP bin. The receiver weight vectors are chosen to optimize an advantageous performance measure. In one embodiment, wherein both the transmitter and receiver have knowledge of the channel state information within each SOP bin, the transmitter spatial weight vectors and the receiver spatial weight vectors are both chosen to optimize performance for a set of multiple substantially independent subchannels within each SOP bin. As discussed above, this significantly increases the spectral efficiency of the system. In another embodiment wherein the transmitter does not have channel state information, the receiver performs the spatial processing required to create multiple substantially independent subchannels within each SOP bin. In a further embodiment wherein the transmitter may or may not have channel state information, the receiver reduces the effects of interference radiated from unintentional transmitters as well as performing the spatial processing required to create multiple substantially independent subchannels within each SOP bin. A yet further embodiment optimizes the receiver spatial vector weights within each SOP bin to simultaneously increase the received power and reduce the detrimental effects of interference received from unintentional transmitters. An additional embodiment involves forming one or more vector weights, that are fixed for all SOP bins, where the vector weights are optimized to simultaneously increase the time or frequency averaged received power for one or more spatial subchannels, while possibly also reducing the time or frequency averaged interference power received from unintended transmitters.

As discussed herein, certain embodiments involve simply passing the vector samples received in each SOP bin to Decoder and Deinterleaving block 150 without performing any spatial processing. It will be obvious to one skilled in the art that other combinations of transmitter spatial weight vector optimization techniques and receiver spatial weight vector optimization techniques can be constructed around the principle concept of spatial processing

in combination with an SOP. Other embodiments are discussed herein. One experienced in the art will be able to recognize additional embodiments that involve advantageous combination of an SOP with spatial processing at the receiver or the transmitter. It is understood that one or more digital filters are typically used in RSFP block 1400 to shape the received RF signal spectrum.

The outputs of RSFP block 140 are fed into Decoder and Deinterleaving (DD) block 150. There are two broad exemplary classes of operation for the DD block 150. In the first exemplary broad class of embodiments, DD block 150 decodes a symbol sequence which was encoded and transmitted through a multitude of SOP bins with one or more substantially independent subchannels. The decoder includes the appropriate receiver counterparts for the combination of encoders selected for the transmitter. A preferred embodiment includes a deinterleaver, a trellis decoder or convolutional bit mapping decoder employing a scalar weighted Euclidean maximum likelihood sequence detector, followed by a Reed Solomon decoder, followed by an ARQ system to correct Reed Solomon codeword errors. In the second exemplary broad class of embodiments, DD block 150 decodes a sequence of multidimensional symbols, or groups of adjacent one dimensional symbols, with each multidimensional symbol or group of one dimensional symbols being received in an SOP bin. Typically, the symbol sequences are transmitted without weighting or with weighting that optimizes some measure of average signal quality.

In an alternative embodiment, trellis encoded symbols are grouped and interleaved in a manner such that the symbols transmitted from the antenna elements within a given SOP bin form a vector that is drawn from either a multidimensional QAM encoder output symbol, or a sequence of one dimensional QAM encoder output symbols that have adjacent locations in the pre-interleaved encoder output sequence. In this way, a maximum likelihood vector decoder may be constructed given an estimate of the channel matrix that is present within each SOP bin. The maximum likelihood decoder computes the weighted vector Euclidean metric given the deinterleaved received vector from each SOP bin, the deinterleaved matrix channel estimates from each SOP bin, and the transmitted vector symbol trellis state table.

In another alternative embodiment, either of the aforementioned encoder embodiments will have preferable performance if the encoder polynomial and symbol constellation set are optimized to improve the bit error rate performance given the characteristics of the matrix channel fading that occurs in each SOP bin. One particular metric that is well suited for a code polynomial optimization search is the product of the two norms of the vector difference between the correct transmitter symbol vector and the error symbol vector.

The output of DD block 150 is the estimated bit stream at the receive end of the radio link.

It is to be understood that all transmitter embodiments of the present invention may be adapted for use with a receiver accessing the channel through a single channel output such as a single receiver antenna element. Furthermore, all receiver embodiments of the present invention may be adapted for use with a transmitter accessing the channel through a single channel input such as a single transmitter antenna element. It is understood that the channel is then a vector channel. Such multiple-input single-output (MISO) and single-input multiple output (SIMO) systems are within the scope of the present invention.

Space-Frequency Communication in a Multipath Channel

Before developing the signal processing of the present invention, a physical description and mathematical description of wireless channels are provided. Many wireless

communication channels are characterized by multi-path, where each path has associated fading and propagation delay. Multipath may be created by reflections in the physical radio path, multiple antenna polarizations, antenna elements located in disparate locations, or a combination of any of these. One scenario in which multipath is created is illustrated in Fig 4.

5 A Base 152 transmits information to and receives information from a remote unit 170A or 170B. Base 152 possesses one or more antenna elements referred to as an array 55. Similarly, the Remote Units possess their own arrays 55. A transmitted signal propagates along multiple paths 155A-C created by reflection and scattering from physical objects in the terrain 160A-D.

10 Multipath signal propagation such as that depicted in Figs. 4-6 can give rise to spatially selective fading, delay spread, frequency fading, and time fading. Spatial fading occurs as the various wavefronts arriving at the receiver from different propagation paths combine with constructive and destructive interference at different points in space. An antenna array located within this spatially selective field will sample the field at various
15 locations so that the signal strength at each array element is different. Delay spread occurs due to the differing propagation path lengths. The channel delay spread gives rise to a frequency selective digital communication channel at each antenna element. This frequency response is different for each antenna element by virtue of the frequency dependent spatial fading. Finally, if either the transmitter, or the receiver, or objects in the terrain are moving,
20 the frequency selective spatial fading will vary as a function of time. The present invention is unique in that it is capable of efficiently and economically adapting to the time varying space-frequency channel response to make advantageous use of the inherent properties of such channels.

For several decades, the primary focus of the prior art has been to somehow mitigate
25 the effects of the multipath channel. This conventional approach is ill-advised since multipath channels give rise to a multiplicative capacity effect by virtue of the fact that the multipath induces a rank greater than one in the matrix channel present in each SOP bin. This provides opportunity to form multiple parallel subchannels for communication within each SOP bin. Thus, one should utilize multipath to improve communication performance rather than
30 attempt to mitigate its effects. A substantial advantage provided by the present invention is the ability to efficiently and economically exploit the inherent capacity advantages of multipath channels using a combination of an SOP and spatial processing or spatial coding. No other structures are known to efficiently exploit this fundamental advantage in the presence of substantially frequency selective multipath channels.

35 Fig. 5 illustrates another wireless channel scenario in which multipath is present. A Base 152 with an antenna array 55 transmits information to and receives information from a Remote 170C with an antenna array 55. In this case, both Base and Remote antenna arrays 55 both have elements with differing polarizations. Thus multipath signal propagation exists even if there are no significant reflections in the physical environment. The direct line of sight
40 paths 155B, 155E each corresponding to one of the polarizations in the array elements, are sufficient to create a matrix channel with a rank greater than one within each SOP bin, even if the other reflected radio paths 155A, 155C, 155D, and 155F are insignificant or nonexistent.

It is known that such line of sight polarization (reflection free) channels can be
45 decomposed into two parallel communication channels by using high performance dual polarization antennas, one at each end of the radio link, in combination with high performance receiver and transmitter electronics apparatus. In this prior art, the quality of the parallel communication channels is limited by the degree to which the two polarization channels remain independent. In general, maintaining the manufacturing tolerances and installation alignment precision in the antennas and electronics required to achieve substantially

orthogonal spatial subchannels at the output of the physical receive antenna is relatively expensive. Slight manufacturing errors and component variations can lead to a significant cross-talk interference between the multiple polarizations present in the radio channel. In contrast, an advantageous feature of the invention is that the different polarizations present in the wireless channel may have an arbitrary degree of cross-talk interference, and the cross-talk interference may be frequency dependent without loss of performance. In such cases, the invention provides an economical and efficient method for fully exploiting the multi-dimensional nature of the multiple polarization channel. It is understood that the invention can provide further capacity advantage if the multiple polarization channel also has reflected signal paths. This additional multipath results in an additional increase in the channel matrix rank in each SOP bin that can be further exploited to improve the capacity of the channel.

Fig. 6 depicts another wireless communication scenario in which multipath is present and can be exploited to create multiple dimensions for communication. In Fig. 6, two Bases 152A and 152B with antenna arrays 55 communicate with Remote Units 170A and 170B that also possess antenna arrays 55. In this case, the composite channel is defined as the MIMO channel between the antennas of the two Bases 152A and 152B and the antennas of the Remote Units 170A and 170B. Note that this channel includes direct line of sight paths 155B and 153B as well as the reflected paths 155A, 155C, 153A, 153C, and 153D. By virtue of the spatial separation between two Bases 152A and 152B, even if the reflected paths are insignificant or nonexistent, this channel contains multipath that can be exploited using the invention. In addition, the channel from the antennas of the two Bases to the antennas of one Remote is again a matrix channel, with rank greater than one, within each SOP bin so that multiple parallel dimensions for transmission may be created. In these types of applications, the present invention provides for the ability to reduce interference radiate to unintentional receivers. Furthermore, the present invention provides the capability of reducing the detrimental effects of received interference from unintentional transmitters.

Thus it can be seen that multiple transmitter antenna elements or multiple antenna elements may be either co-located or be found at disparate locations. The following symbol channel model applies to all of the above multipath radio propagation cases illustrated by Figs. 4-6. The channel impulse response includes the effects of the propagation environment, as well as the digital pulse shaping filters used in TSFP 30 and RSFP 140, the analog filters used in Modulation & RF System 40 and Demodulation & RF System 120. Due to the difference in propagation delay between the various multipath components combined with the time domain response of the RF and digital filter elements, a single symbol transmitted into the channel is received as a collection of delayed copies. Thus, delayed and scaled versions of one symbol interfere with other symbols. This self interference effect is termed intersymbol interference or ISI. The delay spread parameter, denoted by ν , is the duration in symbol periods of the significant portion of the channel impulse response.

As the transmitted symbol rate is increased or as the physical geometries in the channel become larger, the delay spread can become so large that conventional space-time processing systems become highly complex. An advantage of the present invention is that the signal processing complexity is relatively low even when the delay spread becomes extremely large. This allows for the economical application of MIMO space-frequency processing techniques at high digital data rates. This efficient use of signal processing comes about because the invention allows the space-time channel to be treated as a set of substantially independent spatial subchannels without sacrificing channel capacity. In contrast, conventional approaches either attempt to equalize the much more complex space-time channel or alternatively sacrifice capacity.

The channel is modeled as time-invariant over the time spanned by a burst of N data symbols, but varying from one burst to another. This block time invariant assumption produces a channel model that is sufficiently accurate for channels wherein the block duration is short compared to the channel fading, or $(N + 2\nu)T \ll \Delta_\beta$, where Δ_β is the correlation interval¹. Other models are available wherein the channel varies continuously, but these models add unnecessary complication to the present discussion. It is understood that rapid time variation in the channel can be another motivation for choosing one of the other SOP alternatives in the presence of fading rates that are rapid with respect to the burst frequency. One skilled in the art will be aware of the pertinent issues for a given application. For example, Orthogonal Frequency Domain Multiplexing (OFDM) is an SOP composed of an IFFT and cyclic prefix as the transmitter SOP, and an FFT as the receiver SOP. With OFDM, one pertinent issue is frequency domain inter-carrier interference (ICI), which can occur in OFDM systems with extremely rapid fading. Such pertinent issues shape the appropriate choice of channel models for various SOP basis functions.

With this background discussion, it can be verified by one skilled in the art that the relationship between the transmitted burst of baseband symbols and the received burst of baseband samples may be adequately expressed as the space-time equation,

$$\mathbf{x}(k) = \mathbf{G}(k)\mathbf{z}(k) + \mathbf{I}(k),$$

where the index k represents bursts. The composite channel output for one burst of data, $\mathbf{x}(k)$, is written with all time samples appear in sequence for every receive antenna 1 to M_R ,

$$\mathbf{x}(k) = [x_1(1) \ \cdots \ x_1(N + \nu - 1) \ \cdots \ x_{M_R}(1) \ \cdots \ x_{M_R}(N + \nu - 1)]^T.$$

Likewise, the input symbol vector is written,

$$\mathbf{z}(k) = [z_1(1) \ \cdots \ z_1(N) \ \cdots \ z_{M_T}(1) \ \cdots \ z_{M_T}(N)]^T.$$

The quantity $\mathbf{I}(k)$, defined the same as $\mathbf{x}(k)$ and $\mathbf{z}(k)$, represents both noise and interference. The MIMO channel matrix, $\mathbf{G}(k)$, is composed of single-input single-output (SISO) sub-blocks,

$$\mathbf{G}(k) = \begin{bmatrix} \mathbf{G}_{1,1}(k) & \cdots & \mathbf{G}_{1,M_T}(k) \\ \vdots & \ddots & \vdots \\ \mathbf{G}_{M_R,1}(k) & \cdots & \mathbf{G}_{M_R,M_T}(k) \end{bmatrix} \in C^{NM_T \times (N+\nu)M_R}. \quad (1)$$

Furthermore, each of the SISO sub-blocks, $\mathbf{G}_{i,j}(k)$, is a Toeplitz matrix describing the input-output relationship between the transmitted symbol burst and the received symbol burst for antenna pair (i,j) . This MIMO space-time channel is illustrated by Fig. 7, which shows SISO sub-blocks 180A-D and the addition of interference for each receiver sample.

Space-Frequency Processing

Embodiments of the present invention uses space-frequency processing at either the transmitter or receiver, or both, to create effective communication systems in wireless channels. Generally, the processing substantially eliminates the ISI caused by the channel correlation across space (antenna correlation) and time (delay spread). This processing greatly simplifies the design of the remaining functions that comprise a complete

¹ The correlation interval here is defined as the time period required for the fading parameter time-autocorrelation function to decrease to some fraction of the zero-shift value.

communication system, including coding and modulation. Furthermore, the processing approach is based upon a capacity-achieving structure for the MIMO wireless communication channel. Space-frequency processing is composed of one or more of the following: an SOP, a transmit spatial processor, and a receive spatial processor.

Substantially Orthogonalizing Procedure

The use of an SOP in a SISO channel is considered first in order to illustrate the invention's ability to eliminate ISI across space and time. The SOP is composed of signal processing operations implemented at both the transmit and receive sides of the channel. This is illustrated in Fig. 8 where a Transmitter SOP processor 190 and a Receiver SOP processor 200 jointly perform a complete SOP. The SOP ensures that the N input symbols, in bin 1 through bin N , are transmitted through the channel in such a way that each output symbol is substantially influenced by only the input symbol of the same frequency bin. For example, the input symbol in bin 1 is the only symbol to have substantial influence on the output symbol value in bin 1.

This concept generalizes to the MIMO system as shown in Fig. 9. For the MIMO system, each transmitter antenna 51 is preceded by one of M_T identical Transmitter SOP processors. Likewise, each receiver antenna 111 precedes one of M_R identical Receiver SOP processors. Hence, the processing path for any transmitter-receiver antenna pair contains a jointly performed complete SOP. In other words, there exist $M_R M_T$ SISO SOPs in the MIMO system. By exploiting the property of superposition, this collection of SISO SOPs comprise a MIMO SOP where any two symbols communicated in different bins exhibit substantially reduced crosstalk, irrelevant of the antennas by which the symbols were transmitted and received. Therefore, the SOP establishes N substantially independent MIMO spatial channels.

Many different SOP implementations exist, including an IFFT-FFT pair, a bank of multiple narrow-band filters, and generalized wavelet transform pairs. One advantageous example of an SOP is the use of a frequency transform combined with a burst cyclic prefix application procedure processor 207, as shown in Fig. 10. There is also a cyclic prefix removal procedure processor 206 at the receive end. When the frequency transform is an IFFT-FFT pair 205 and 208 as shown in Fig. 10, this particular SOP is commonly referred to as discrete orthogonal frequency division multiplexing (OFDM). Hence, this embodiment of the invention combines the OFDM SOP with multiple input antennas, or multiple output antennas, or both multiple input and multiple output antennas. The present embodiment is thus termed matrix-OFDM (MOFDM).

The analysis presented for MOFDM will have a substantially similar form as other choices for the SOP. These alternative embodiments have certain advantages and drawbacks as compared to the OFDM SOP. For example, the multi-band SOP does not completely eliminate ISI, but it is more robust to certain types of narrow-band interfering signals because the interference can be more confined within a given SOP bin as compared to the OFDM SOP. The ISI that can be present in the multi-band SOP could make it advantageous to use pre-equalization or post-equalization structures in conjunction with the spatial processing within a given SOP bin. While this complicates the spatial processing, the complexity drawback may be outweighed by other requirements such as robustness to interference or the need to separate the SOP bins by relatively large frequency separation. Only the OFDM SOP will be analyzed in detail herein and it will be understood that one may exploit the other SOP choices as needs dictate.

As depicted in Fig. 10, the exemplary SOP operates in the following fashion. The symbols from the transmit spatial pre-processor, $z_j(n)$, considered to be in the frequency

domain, are organized into M_T vectors of N complex symbols. Each of these vectors is then converted to the time-domain using an N -point inverse-fast-Fourier-transform (IFFT) procedure 205. Each of the parallel M_T time-domain sequences has a cyclic prefix added to the beginning, so that the last ν elements in the IFFT output sequence form a pre-amble to the N -element IFFT output. The cyclic prefix operation is given by:

$$[z(1) \ \cdots \ z(N)]^T \mapsto [z(N-\nu+1) \ \cdots \ z(N) \ z(1) \ \cdots \ z(N)]^T$$

The application of the cyclic prefix is performed by cyclic prefix application procedure processor 207. For each antenna, the $(N + \nu)$ -length sequences are passed to the RF transmit chain for D/A conversion and modulation.

Likewise, each RF receiver chain produces a sampled sequence of length $N + \nu$. Cyclic prefix removal procedure processors 206 remove the cyclic prefix from each sequence by discarding the first ν data symbols, resulting in M_R vectors of N complex symbols. Each of these M_R sequences is then processed with an N -point fast-Fourier-transform (FFT). These symbols are then passed to the receiver spatial processor.

The effect of the SOP is to substantially remove the ISI between any two symbols assigned to different bins, for any pair of transmit and receive antennas. Therefore, for each IFFT-FFT bin n , the received signal values for each antenna, $\mathbf{x}(n)$, are related to the transmitted frequency-domain symbols, $\mathbf{z}(n)$, through the expression,

$$\mathbf{x}(n) = \mathbf{H}(n)\mathbf{z}(n) + \mathbf{I}(n) \quad \forall n \quad (10)$$

where $\mathbf{x}(n)$ is a complex M_R -element vector at SOP bin n , $\mathbf{z}(n)$ is a complex M_T -element symbol vector at bin n , and $\mathbf{I}(n)$ is the interference and noise at all receive antennas for bin n . Note that a time index is not included in the above equation since it is assumed that channel is time-invariant over the length of a burst. The spatial sub-channels, $\mathbf{H}(n)$, are M_R by M_T element matrices that describe the spatial correlation remaining in the wireless channel after the SOP. For the MIMO case, each SOP bin may be characterized by a matrix of complex values, with each value representing the path gain from a given transmit antenna element to a given receive antenna element in that particular SOP bin.

To understand the result given by Equation(10), it is instructive to show how the SOP pre-processor and post-processor acts upon the time-domain channel. The MIMO time-domain channel, $\mathbf{G}(k)$, contains $M_R M_T$ Toeplitz matrices that describe the time-domain input-output behavior of each antenna pair (see eq. 1). This channel formulation is depicted in Fig. 10. It is well known that by adding a cyclic prefix at the transmitter and subsequently removing the prefix at the receiver, a Toeplitz input-output matrix is transformed into a circulant input-output matrix (the i th row is equal to the j th row cyclicly shifted by $i-j$ elements). Therefore, the each $\mathbf{G}_{i,j}$ in Fig. 10 is transformed into a circulant $\tilde{\mathbf{G}}_{i,j}$. The MIMO circulant matrices are delimited in Fig. 10 by $\tilde{\mathbf{G}}$.

This particular class of SOP exploits the fact that any circulant matrix can be diagonalized by a predetermined matrix operator. One such operator is a matrix of the FFT basis vectors. That is, for any circulant matrix $\tilde{\mathbf{G}}$,

$$\mathbf{D} = \mathbf{Y}\tilde{\mathbf{G}}\mathbf{Y}^H$$

where \mathbf{D} is some diagonal matrix and the scalar elements of \mathbf{Y} are,

$$y_{mn} = \frac{1}{\sqrt{N}} e^{-j2\pi mn/N}.$$

Applying M_T IFFT operations at the transmitter and M_R FFT operations at the receiver is described mathematically by a pre-multiplication of a $NM_R \times NM_R$ block diagonal FFT matrix

and post-multiplication of a $NM_T \times NM_T$ IFFT matrix. For example, the former matrix is defined,

$$\mathbf{Y}_{(M_R)} = \begin{bmatrix} \mathbf{Y} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{Y} \end{bmatrix}.$$

Therefore, including the transmitter IFFT and receiver FFT operations, the input-output relationship is described by

$$\mathbf{Y}_{(M_R)} \tilde{\mathbf{G}} \mathbf{Y}_{M_T}^H = \begin{bmatrix} \mathbf{D}_{1,1} & \cdots & \mathbf{D}_{1,M_T} \\ \vdots & \ddots & \vdots \\ \mathbf{D}_{M_R,1} & \cdots & \mathbf{D}_{M_R,M_T} \end{bmatrix},$$

where $\mathbf{D}_{i,j}$ is the diagonal matrix containing the SOP bin strengths for the antenna pair (i,j) .

Pre-multiplication and post-multiplication by permutation matrices \mathbf{P}_T and \mathbf{P}_R represents the collection of all antenna combinations that correspond to a common frequency or SOP bin.

This collection process, depicted in Fig. 10, results in a block diagonal matrix that relates the inputs and outputs:

$$\mathbf{P}_R \mathbf{Y}_{(M_R)} \tilde{\mathbf{G}} \mathbf{Y}_{M_T}^H \mathbf{P}_T = \begin{bmatrix} \mathbf{H}(1) & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{H}(N) \end{bmatrix},$$

which is equivalent to Equation (10).

Spatial Processing

The spatial processing procedure is now considered. Since the SOP establishes N MIMO spatial channels that are substantially independent from one another (Equation 10), one can consider the spatial processing within each bin separately. Representative application of spatial processing to frequency bin 1 will be considered as shown in Fig. 11 at the transmitter and Fig. 12 at the receiver. Fig. 11 shows M symbols: $z(1,1)$ through $z(1,M)$. The notation $z(n,m)$ refers to the symbol transmitted in bin n and spatial direction m . These M symbols will jointly occupy frequency bin 1. Each TSW 210A-C applies a weight vector to the symbol appearing at its input, and the elements of the resultant vector are routed to M_T summing junctions 211. One may consider the TSWs as being multipliers taking each input symbol and multiplying it by a vector that corresponds to a spatial direction in M_T -space. Furthermore, the M vectors define a subspace in M_T -space. Note that the TSW vectors are considered to be column vectors in the discussion that follows. When these M vectors are collected into a matrix, the result is an input orthogonalizing matrix or beneficial weighting matrix for that bin. For each input bin, a vector including symbols allocated to subchannels corresponding to the bin is multiplied by the input orthogonalizing matrix to obtain a result vector, elements of the result vector corresponding to the various transmitter antenna elements. Together, the TSWs 210A-C make up one embodiment of a Transmit Spatial Processor (TSP) 230.

Each RSW 220A-C accepts M_R inputs, one from each receiver antenna path. Within the m^{th} RSW, a weight vector is applied to the inputs (i.e. an inner-product is performed) thereby producing a received signal sample $x(1,m)$:

$$x(1, m) = \mathbf{u}(1, m) \begin{bmatrix} x_1(1) \\ \vdots \\ x_{M_R}(1) \end{bmatrix},$$

where $\mathbf{u}(1, m)$ is the RSW for bin 1 and spatial direction m . Similar to a TSW, a RSW vector has an associated direction in M_R -space. Each RSW may also be considered to be a multiplier. This vector is considered to be a row vector. When these M RSW vectors are collected into a matrix, the result is an output orthogonalizing matrix or beneficial weighting matrix for that bin. When a vector including symbols in a particular output bin produced by the SOP for each receiver antenna is multiplied by the output orthogonalizing matrix, the result is a vector including symbols received in that bin for various spatial directions. Together, the RSWs 220A-220C represent one embodiment of a Receive Spatial Processor (RSP) 240.

Through proper choice of the weight vectors applied via the TSWs and RSWs, the M spatial directions can be made substantially orthogonal to one another. The result is that the received signal sample $x(1, m)$ depends only upon input symbols $z(1, m)$ and not the $M-1$ other input symbols for SOP bin 1. Methods for selecting the TSP and RSP weight vectors are described in detail below.

The spatial processing described above can be applied to the other $N-1$ frequency bins in addition to frequency bin 1. The block diagram for such a system is depicted in Fig. 13 for the transmitter and Fig. 14 for the receiver. SOP processors 190 and 200 ensure that the frequency bins remain substantially orthogonal to one another while TSP 230 and RSP 240 ensure that M substantially orthogonal spatial channels exist within each frequency bin. The net result is that NM substantially parallel subchannels are constructed within the MIMO communication system. In other words, the combination of SOP processors 190 and 200, TSP 230, and RSP 240 create a set of substantially independent space-frequency subchannels,

$$x(n, m) = H(n, m)z(n, m) + I(n, m) \quad \forall n, m.$$

This simultaneous substantial orthogonalization of space and frequency can result in a significant increase in spectral efficiency since multiple data streams are being communicated through the channel. Note that the number of substantially independent subchannels possible, in the multipath case, is equal to the number of SOP bins multiplied by the number of transmit antennas or the number of receive antennas, whichever is smaller. Therefore, the total number of space-frequency subchannels is less than or equal to $N \min(M_T, M_R)$, when multipath is present.

An exemplary set of TSWs and RSWs are derived from the singular value decomposition (SVD) of the spatial channel matrix for each bin,

$$\mathbf{H}(n) = \mathbf{U}(n)\mathbf{\Sigma}(n)\mathbf{V}(n)^H.$$

The input singular matrix, $\mathbf{V}(n)$, contains M_T column vectors that define up to M_T TSWs for bin n . Likewise, the output singular matrix, $\mathbf{U}(n)$, contain M_R column vectors that when Hermitian transposed, define up to M_R RSW row vectors for bin n . The TSWs and RSWs for other bins are determined in the same fashion, through an SVD decomposition of the spatial matrix for that bin. Using this spatial processing, substantially independent multiple streams of symbols can be transmitted and received. The strength of each subchannel is equal to one of the elements of the diagonal matrix $\mathbf{\Sigma}$. These subchannels strengths will vary. Therefore, the subchannels will have varying signal to noise ratios and information capacity. For this reason, it may be preferable to transmit and receive only on a subset of the possible subchannels, or $M < \min\{M_T, M_R\}$. For example, it may be improvident to use processing

complexity on the weakest subchannels that may have a very small information carrying capacity. In this case, spatial processing is used to increase the received power of one or more parallel symbol streams. It may also be preferable to use coding techniques to leverage strong subchannels to assist in the use of weaker subchannels. It may also be preferable to allocate either bits or transmit power among the subchannels to maximize the amount of information communicated.

The exemplary spatial processing described above requires cooperation between the transmitter and receiver to effectively orthogonalize the spatial channel for each bin. Alternatively, this orthogonalization can be accomplished at only one end of the link. This can be advantageous when one end of the link can afford more computational complexity than the other end. In addition, spatial orthogonalizing at one end can be advantageous when the channel model is known only at that end.

Consider the case where the orthogonalization is done at the receiver. Symbols are transmitted along directions defined by some set of TSWs, $\mathbf{v}(n,m)$. When M TSWs corresponding to the same bin are collected into a matrix $\mathbf{V}(n)$, the composite spatial channel is,

$$\mathbf{H}'(n) = \mathbf{H}(n)\mathbf{V}(n).$$

This composite channel describes the MIMO channel in bin n from the M -inputs to M_R outputs. The spatial processing at the receiver can substantially orthogonalize this composite channel, $\mathbf{H}'(n)$, by applying appropriate RSWs even if the transmitter does no spatial processing. Let these RSWs be defined as the row vectors of the weighting matrix, $\mathbf{W}_R(n)$.

Two exemplary methods for determining $\mathbf{W}_R(n)$ are referred to as the zero-forcing (ZF) solution and minimum-mean-square-error (MMSE) solution. In the ZF approach, the weighting matrix is the pseduo-(left)-inverse of the composite channel,

$$\mathbf{W}_R(n) = \mathbf{H}'(n)^\perp.$$

This results in,

$$\mathbf{W}_R(n)\mathbf{H}'(n) = \mathbf{I},$$

where the identity matrix is M by M . Hence, the ZF solution, not only orthogonalizes the spatial channel for bin n , but it equalizes the strengths of each resulting subchannel. However, the signal-to-noise ratio for the various subchannels can vary widely. One skilled in the art will recognize that the ZF solution can result in amplification of the interference and noise unless the composite channel, $\mathbf{H}'(n)$, is nearly orthogonal to begin with.

An MMSE solution, on the other hand, does not amplify noise. For the MMSE approach, the weight, $\mathbf{W}_R(n)$, satisfies,

$$\min_{\mathbf{W}_R(n)} E \left\{ \left\| \mathbf{W}_R(n)\mathbf{x}(n) - \mathbf{z}(n) \right\|^2 \right\},$$

or,

$$\mathbf{W}_R(n) = \mathbf{R}_{\mathbf{z}(n)\mathbf{x}(n)} \mathbf{R}_{\mathbf{x}(n)}^{-1},$$

where $\mathbf{R}_{\mathbf{x}(n)}$ is the covariance matrix for $\mathbf{x}(n)$ and $\mathbf{R}_{\mathbf{z}(n)\mathbf{x}(n)}$ is the cross-covariance between $\mathbf{z}(n)$ and $\mathbf{x}(n)$. Using,

$$\mathbf{x}(n) = \mathbf{H}'(n)\mathbf{z}(n) + \mathbf{I}'(n),$$

and the fact that $\mathbf{R}_{\mathbf{z}(n)} = \sigma_z^2 \mathbf{I}$, results in the MMSE weight,

$$\mathbf{W}_R(n) = \mathbf{H}'(n)^H \left(\mathbf{H}'(n)\mathbf{H}'(n)^H + \frac{1}{\sigma_z^2} \mathbf{R}_{\mathbf{I}'} \right)^{-1}.$$

Note that when $\mathbf{I}(n)$ is spatially white noise, then $\mathbf{R}_I = \sigma_I^2 \mathbf{I}$.

Similarly to the above orthogonalization at the receiver, the channel can be orthogonalized at the transmit end only. For this to occur, the transmitter is required to have knowledge of the RSWs to be used by the receiver. In a TDD channel, where the channel exhibits reciprocity, these RSWs can be learned when that transceiver uses TSW directions equal to the RSW directions. Alternatively, the receiver may not do any spatial processing, so the transmitter is responsible for spatial orthogonalization.

In this case, the composite channel is

$$\mathbf{H}'(n) = \mathbf{U}(n)\mathbf{H}(n),$$

where the matrix $\mathbf{U}(n)$ is composed of the RSW row vectors, $\mathbf{u}(n,m)$. This composite channel describes the MIMO channel in bin n from M_T inputs to M outputs. Similar to the previous case, the transmitter can substantially orthogonalize this composite channel, $\mathbf{H}'(n)$, by applying appropriate TSWs. These TSWs are the column vectors of the weighting matrix, $\mathbf{W}_T(n)$.

The transmit weighting can be determined using the ZF or the MMSE approach. In the ZF approach, the weighting matrix is equal to the pseudo-(right)-inverse of $\mathbf{H}'(n)$. The MMSE solution satisfies

$$\min_{\mathbf{W}_T(n)} E \left\{ \left\| \mathbf{H}'(n)\mathbf{W}_T(n)\mathbf{z}(n) + \mathbf{I}'(n) - \mathbf{z}(n) \right\|^2 \right\},$$

An important simplification to the general space-frequency processing technique is the use of only one spatial direction for each bin of the SOP. This case is depicted in Fig. 15 for the transmitter and Fig. 16 for the receiver. In this case, only N subchannels are created. The N input symbols, $z(1,1)$ through $z(N,1)$, are processed by N TSWs 210A-B that weight and allocate these N symbols among the M_T identical SOP processors 190. At the receiver, the antenna samples are processed by M_R SOP processors 200. The M_R SOP outputs corresponding to a common bin are weighted and combined in N RSWs 220A-B. With N such weightings, the result is N outputs, $x(1,1)$ through $x(N,1)$, of the N substantially orthogonal subchannels.

When only one spatial direction is used in the TSP and RSP, one exemplary choice for the particular weightings are the TSW and RSW directions that result in maximum subchannel strength. This maximizes the signal-to-noise ratio (SNR) of the received signals, $x(1,1)$ through $x(N,1)$. In this case, the optimal weightings should satisfy,

$$\max_{\mathbf{u}(n), \mathbf{v}(n)} \left| \mathbf{u}(n)\mathbf{H}(n)\mathbf{v}(n) \right|^2,$$

with the implicit constraint on the size (2-norm) of both the RSW weight $\mathbf{u}(n)$ and the TSW weight $\mathbf{v}(n)$. To determine the solution to this optimization problem, consider the SOP outputs for bin n when a single TSW, $\mathbf{v}(n,1)$, is used,

$$\begin{bmatrix} x_1(n) \\ \vdots \\ x_{M_R}(n) \end{bmatrix} = \mathbf{H}(n)\mathbf{v}(n,1)z(n,1) = \mathbf{h}(n)z(n,1).$$

The quantity $\mathbf{h}(n)$ is referred to as the received channel vector. A channel identification technique is used to determine the received channel vector. Therefore, the optimal RSW weight is equal to the Hermitian of the received channel vector, $\mathbf{h}(n)$,

$$\mathbf{u}(n) = \mathbf{h}(n)^H.$$

- 5 Note that this is true regardless of the particular value of $\mathbf{v}(n)$. The optimal TSW direction, on the other hand, satisfies,

$$\max_{\mathbf{v}(n)} \mathbf{u}(n)\mathbf{H}(n)\mathbf{v}(n) = \max_{\mathbf{v}(n)} \mathbf{v}(n)^H \mathbf{H}(n)^H \mathbf{H}(n)\mathbf{v}(n),$$

where the optimal RSW direction has been used. The optimal TSW for bin n is equal to the scaled maximum eigenvector of the matrix $\mathbf{H}(n)^H \mathbf{H}(n)$. One skilled in the art will recognize

- 10 that the optimal RSW is also equal to the scaled maximum eigenvector of $\mathbf{H}(n)\mathbf{H}(n)^H$.

A further advantageous simplification of the above techniques is the use of one or more common TSW and RSW directions for all bins. In other words, every bin has the same TSW and RSW weights. These weight vectors may also consider delay elements. In one embodiment, these weights are determined to maximize the SNR of the received signals, averaged over frequency n . This is depicted in Fig. 17 for the transmitter and Fig. 18 for the receiver. Consider this embodiment with one spatial direction. In this case, the TSW and RSW weights satisfy,

$$\max_{\mathbf{u}, \mathbf{v}} E_n [\mathbf{u}\mathbf{H}(n)\mathbf{v}]^2, \quad 50$$

- 20 Note that the expectation operator, E_n , represents averaging over SOP bins. This averaging could also be done over multiple bursts in addition to frequency. The solution to this problem is when \mathbf{v} is equal to the maximum eigenvector of

$$\mathbf{R}_d = E_n \{\mathbf{H}^H(n)\mathbf{H}(n)\}, \quad 51$$

and \mathbf{u} is equal to the maximum eigenvector of the covariance matrix formed from averaging the outer product of the receive vector channel,

$$\mathbf{R}_h = E_n \{\mathbf{h}(n)\mathbf{h}(n)^H\}. \quad 52$$

The quantity \mathbf{R}_d is the spatial covariance matrix that describes preferable directions to transmit to the desired receiver, a desired subspace.

- 30 This technique can be generalized to the case where multiple directions are utilized. In this case, M TSWs and M RSWs are determined to maximize the average (over bin) SNR received through the M spatial directions. The M spatial directions will not necessarily be orthogonal to each other. Therefore, there will be spatial crosstalk in the received symbols. Multidimensional encoding and decoding techniques discussed below can then achieve a multiplicative rate increase in the presence of such crosstalk.

- 35 Alternatively, the receiver can spatially orthogonalize the subchannels by further weighting of the M outputs from the RSWs. The composite spatial channel at bin n , with the RSWs and TSWs included is

$$\mathbf{H}'(n) = \mathbf{U}\mathbf{H}(n)\mathbf{V}, \quad 53$$

- 40 where the matrix \mathbf{U} is made up rows equal to the RSW directions and \mathbf{V} is a matrix with columns equal to the TSW directions. Since \mathbf{U} and \mathbf{V} were determined based on an average SNR criterion for all bins, the composite matrix $\mathbf{H}'(n)$ will not be diagonal. Hence, the receiver can apply the additional weight, $\mathbf{W}_R(n)$, to orthogonalize $\mathbf{H}'(n)$. Alternatively, the transmitter can use the additional weight, $\mathbf{W}_T(n)$, to spatially orthogonalize the composite channel. Exemplary solutions for these weightings are the joint SVD, the ZF and MMSE. The advantage of this approach is that the processing required to adapt all N SOP bin matrix

channels may be substantially higher than the processing complexity to adapt the average TSP and RSP.

The rejection and prevention of interference can be accomplished in conjunction with the space-frequency processing discussed above. This is especially useful when the number of spatial directions used for communication is less than the number of antennas. This case occurs when weak spatial directions are not utilized or when the number of antennas at the receiver and transmitter are not the same. In either case, one or both ends of the communication link have extra spatial degrees of freedom to use for the purpose of mitigating interference.

The amount of interference arriving at an antenna array can be quantified by the interference covariance matrix,

$$\mathbf{R}_I(n) = E\{\mathbf{I}(n)\mathbf{I}(n)^H\},$$

where $\mathbf{I}(n)$ is the M_R length interference plus noise vector received in SOP bin n . This matrix defines an undesired interference plus noise subspace in M_R -space for bin n . The interference plus noise energy that contaminates a particular received subchannel symbol with bin n and spatial direction m , is equal to,

$$\mathbf{u}^H(n, m)\mathbf{R}_I(n)\mathbf{u}(n, m),$$

where $\mathbf{u}(n, m)$ is the combining weight vector for the RSP(n, m). An advantageous interference rejection technique is then to “whiten” the effect of the interference across the spatial directions, so that the interference is minimized and spread evenly across all spatial directions used. Therefore, each of the RSP weighting vectors are modified by the matrix $\mathbf{R}_I^{-1/2}(n)$,

$$\mathbf{u}'(n, m) = \mathbf{u}(n, m)\mathbf{R}_I^{-1/2}(n).$$

Alternatively, the RSP weighting vectors are the vectors of the output singular matrix, $\mathbf{U}'(n)$, from the SVD of the modified spatial channel,

$$\mathbf{R}_I^{-1/2}(n)\mathbf{H}(n) = \mathbf{U}'(n)\mathbf{\Sigma}'(n)\mathbf{V}'(n)^H.$$

Note that a very useful simplification of the above interference rejection technique is to average the interference covariance matrix over all N bins and possibly a set of bursts to arrive at an average spatial interference covariance matrix, \mathbf{R}_I , that is independent of bin n .

In this case, every RSP combining vector is modified in the same way due to interference. This approach can significantly reduce the amount of computations needed to determine \mathbf{R}_I and $\mathbf{R}_I^{-1/2}$. Note that it is often beneficial to add a scaled matrix identity term to estimates of the interference covariance matrix to reduce the sensitivity of these interference mitigation approaches to covariance estimation errors.

Similar interference mitigation techniques can be advantageously employed at the transmitter to reduce the amount of interference radiated to unintentional receivers. In the TDD channel, reciprocity in the radio link allows the undesired receive interference subspace in each SOP bin to be accurately used to describe the transmitter subspace. That is, the amount of interference transmitted to unintentional receivers is

$$\mathbf{v}^H(n, m)\mathbf{R}_I(n)\mathbf{v}(n, m), \quad 60$$

where $\mathbf{v}(n, m)$ is the transmit weight vector for the TSW(n, m). An optimal interference reduction approach is then to minimize and “whiten” the transmitted interference across spatial directions. In the same fashion as the receiver case, the TSW vectors are modified by the matrix $\mathbf{R}_I^{-1/2}(n)$. Alternatively, the TSP weight vectors are the vectors of the input singular matrix $\mathbf{V}'(n)$ from the SVD of the modified spatial channel,

$$\mathbf{H}(n)\mathbf{R}_I^{-1/2}(n) = \mathbf{U}'(n)\Sigma'(n)\mathbf{V}'(n)^H. \quad 61$$

Again, a significant simplification occurs when the interference covariance matrix is determined by averaging over frequency or SOP bins. It is especially advantageous to average over SOP bins in a frequency-division-duplex (FDD) system, where significant averaging of the receive covariance matrix results in a good estimate of the transmit covariance, even though instantaneous channel reciprocity does not hold.

Interference rejection at the receiver and interference reduction at the transmitter are done together by simply combining the two techniques outlined above. In this case, the RSP vectors and TSP vectors are contained in the input and output matrices of the SVD of,

$$\mathbf{R}_{I,R}^{-1/2}(n)\mathbf{H}(n)\mathbf{R}_{I,T}^{-1/2}(n).$$

As outlined previously, it can be advantageous to use the same TSWs and RSWs for all bins. This approach can be combined with interference mitigation by the determining the transmit and receive weight vectors that maximize average power delivered to the receiver of interest, while at the same time, minimizing power delivered to other undesired receivers. There are various optimization problems that can be posed to determine these TSP or RSP directions, each involving the desired receiver covariance matrix and the undesired covariance matrix. For example, one TSP problem is

$$\max_{\mathbf{v}} \mathbf{v}^H \mathbf{R}_d \mathbf{v} \quad \text{such that} \quad \mathbf{v}^H \mathbf{R}_I \mathbf{v} \leq P_I \quad \text{and} \quad \mathbf{v}^H \mathbf{v} \leq P_T.$$

That is, a TSP direction is chosen for all SOP bins that transmits the maximum amount of power to the desired receiver while maintaining a transmit power limit, P_T , and a transmitted interference limit, P_I . For this particular problem, the TSP direction is equal to the maximum generalized eigenvector of the matrix pair $\{\mathbf{R}_d, (\mathbf{R}_I / P_I + \mathbf{I} / P_T)\}$. One example of an effective interference rejecting RSP for all SOP bins is a weighing that maximizes the average received SINR. The RSP that maximizes SINR is the maximum eigenvector of the matrix $\mathbf{R}_I^{-1/2} \mathbf{R}_d \mathbf{R}_I^{-1/2}$.

One further simplification to the above algorithm is to model the interference and/or the desired covariance as diagonal, or nearly diagonal. When both \mathbf{R}_d and \mathbf{R}_I are diagonal, the solution to the above optimization problem reduces to the maximal ratio SINR combiner, \mathbf{u} , and transmitter, \mathbf{v} . It is also sometimes preferable to only consider other subsets of the elements of either the desired or interference covariance matrices.

One skilled in the art will also recognize that all the TSPs and RSPs can be used when there is only one SOP bin, such as a common frequency.

Space Frequency Coding

Many of the advantageous space frequency encoding techniques embodied in the invention may be broadly classified in two exemplary categories. The first category involves techniques wherein the spatial matrix channel within each SOP bin undergoes space frequency processing at the transmitter, or the receiver or both, resulting in a substantially independent set of one or more parallel communication subchannels within each SOP bin. The objective of the encoder and decoder in this case is to appropriately allocate the transmitted information among multiple independent space-frequency subchannels using interleaving, power and bit loading, or both. The second category of space frequency encoding involves transmitting and receiving one or more symbol sequences in each SOP bin using one or more transmitter and receiver weight vector combinations that are not necessarily intended to create independent spatial subchannels within each SOP bin. This results in significant cross-talk between each symbol stream present at the receiver output. A decoder then uses knowledge of the

equivalent matrix channel within each SOP bin, and knowledge of the set of possible encoder sequences to estimate the encoder symbol sequence that gave rise to the cross-talk rich output SOP bin vector sequence. The main differentiating feature between the first approach and the second approach is the presence or lack of spatial processing that results in substantially orthogonal spatial subchannels within each SOP bin. Both approaches have the advantageous ability to multiply the data rate that can be achieved in MIMO channels with multipath.

Coding for Substantially Orthogonal Space-Frequency Subchannels

In applications where the spatial channels are processed to achieve multiple substantially independent spatial subchannels within each SOP bin, an advantageous embodiment of the invention involves encoding the input data sequence into a digital symbol stream that is then routed in various beneficial ways through the available parallel space frequency subchannels. Fig. 22 depicts a preferred embodiment. This embodiment involves distributing the symbol outputs of a single encoder among all of the available space frequency subchannels. Several known coding schemes that can be combined effectively with space frequency processing to distribute information transmission over the space and frequency dimensions of a communication channel. This discussion assumes estimation of the MIMO channel by transmitting a series of training symbol sequences from each antenna element as discussed herein. The discussion further assumes that the receiver and transmitter either share the information required to decompose the channel into parallel sub-channels, or the TDD techniques discussed herein are used to do the same.

Referring again to Fig. 22, the preferred embodiment exploits a three layer coding system. The first layer of coding includes the combination of transmitter TSWs 210A through 210B, Transmitter SOP processors 190, receiver SOP processors 200, and receiver RSWs 220A through 220B. This first layer of coding performs the spatial processing. The second layer of coding includes a Trellis Encoder and Interleaver (420) at the transmitter in combination with a Deinterleaver and ML Detector 430 at the receiver. The third layer code involves Reed Solomon (RS) Encoder 410 at the transmitter in combination with an RS Decoder 440 at the receiver. The bit level RS coding occurs prior to the trellis encoding and the Reed Solomon codeword detector acts upon the bit sequence from the ML detector. The fourth layer of coding involves an ARQ code that recognizes Reed Solomon codeword errors at the receiver in the Receiver ARQ Buffer Control 450 and requests a codeword retransmission from the Transmitter ARQ Buffer Control 400. The retransmission request is made through a Reverse Link Control Channel 460. The reverse control channel is a well known radio system concept and will not be discussed herein. This combination of coding techniques and space frequency processing is preferable because it provides for a rich combination of space and frequency diversity and it is capable of obtaining very low bit error rates. The detailed operation of the RS encoder and decoder, as well as the ARQ system is well known to one skilled in the art. Following this discussion, it will be clear to one skilled in the art that other combinations of one or more of these four coding elements may be employed with advantageous results in various applications.

The trellis coding step may be substituted with CBM-QAM or a turbo code. Similarly, the Reed-Solomon code may be substituted with a block code, or with an error checking code such as a CRC code. The transmitter end would then include the necessary encoder and the receiver end would include the necessary decoder.

There are at least two basic methods for employing trellis coding to distribute information among substantially independent space frequency subchannels. One method is adaptive encoding that modifies the bit and power loading for each subchannel according to its

quality. The second method involves maintaining constant power and bit loading for all space frequency subchannels. Both of these methods are discussed below.

Space Frequency Trellis Coding with Orthogonal Spatial Subchannels and Adaptive Power and Bit Loading

Fig. 22 depicts the coding and interleaving detail for the transmitter and receiver portions of the present embodiment. Encoding and Interleaving system 10 encodes the data into a set of complex symbols. Each of the complex symbols is then allocated to a particular transmitter TSW (210A through 210B). The input to each TSW forms a vector of frequency domain symbols that are fed into the same bin of one or more transmit SOP processors. Each transmitter TSW, possibly in conjunction with a receiver RSW converts the matrix channel within each SOP bin into a set of substantially orthogonal space frequency subchannels using one of the methods discussed herein.

Fig. 23 displays a more detailed diagram of the encoder and interleaver. An Information Allocation Unit 360 assigns the bits and the transmitter power that will be allocated to each space frequency subchannel. One method for accomplishing this assignment is the so-called gap analysis. In this technique, a particular coset code with an associated lattice structure is characterized by first determining the SNR required to achieve a theoretical capacity equal to the desired data rate. The code gap is then the SNR multiplier required to achieve the target probability of error at the desired data rate. In a parallel channel communication system, this gap can be used to determine the power and bit distributions that maximize data rate subject to a probability of error constraint. With a coding gap of α , the rate maximizing water-filling solution for the space frequency subchannels becomes

$$p(n, m) = \left(\xi - \frac{\sigma_n^2 \alpha}{|\lambda(n, m)|^2} \right)^+,$$

where σ_n^2 is the noise power and m is the spatial index and n is the DFT frequency index.

The bit allocation per sub-channel is then given by

$$b(n, m) = \log \left(1 + \frac{p(n, m) \cdot |\lambda(n, m)|^2}{\alpha \sigma_n^2} \right).$$

After the power and bit loading assignments are accomplished in the Information Allocation Unit, the bits are encoded with a Trellis Encoder 370. It is not possible to achieve infinite bit resolution (granularity) with coset codes. Therefore the gap analysis solution should be modified. Several bit loading algorithms exist to resolve this problem. One method involves rounding down the water filling solution to the nearest available quantization. The granularity of possible bit allocations is determined by the dimensionality of the coset code lattice structure. In the MIMO channel communication structures described herein, the orthogonal constellation dimensions are the complex plane, space, and frequency.

Fig. 26 illustrates an example of a practical method for bit loading with a trellis encoder that uses a one dimensional QAM symbol constellation. The bit load is adjusted down for a given trellis encoder output symbol by assigning a number of fixed zeros to one or more of the input bits to the encoder. Fig. 26 shows the operation of the trellis encoder and the trellis state diagram for the decoder for four successive symbol transmissions. Four bits are assigned to the first space frequency subchannel. A first subchannel trellis encoder input 350 is assigned 4 bits so Symbol 1 can take on any one of 32 values. There are two bits feeding the convolutional encoder, and two bits feeding the coset select. The ML detector at

the receiver uses the trellis state diagram and the channel state information to solve the maximum likelihood recursion. This is efficiently accomplished with the Viterbi algorithm. The trellis code state diagram defines a set of symbol sequence possibilities $\{Z\}$. The space frequency subchannel is denoted $\hat{H}(n, k)$, for SOP bin n at burst k . The maximum likelihood equation is then given by

$$\{\hat{z}(1)^T, \hat{z}(2)^T, \dots, \hat{z}(N)^T\} = \arg \left\{ \min_{z=\{z(1)^T, z(2)^T, \dots, z(N)^T\}} \sum_{n=1}^N |\hat{H}(n, k)z(n) - x(n, k)|^2 \right\}$$

where $z(n)$ is the symbol hypothesized for SOP bin n . The decoder output state diagram for first space frequency subchannel 340 includes four possible parallel transitions for each trellis branch and all of the trellis branches are possible. The second space frequency subchannel in the sequence is assigned three bits so a second trellis encoder input 352 shows one bit fed into the coset select with two bits still feeding the convolutional encoder. A decoder state diagram 342 for the second space frequency subchannel has only two parallel transitions for each trellis branch but still maintains all trellis branch possibilities. Continuing in succession, a third space frequency subchannel is assigned only two bits to an encoder input 354 so there are no parallel transitions considered by a trellis decoder state diagram 344. In a fourth space frequency subchannel, only one bit is assigned to an encoder input 356 so there are no parallel transitions and some of the trellis state branches (346) are no longer considered by the decoder. It is understood that Fig. 26 is provided as a graphical aid and is not intended to represent an actual design.

The maximum Euclidean distance error sequence design metric is one preferable choice for a trellis encoder used with the parallel space frequency channel with this bit and power loading embodiment of the invention. Other code error sequence design metrics that are advantageous in various application conditions include product distance and periodic product distance.

Referring again to Fig. 23, the output of the encoder is interleaved across the various space frequency subchannels using Interleaving block 260. Typically, the interleaving process distributes the symbols so that symbols that are near one another at the encoder output are well separated in both the SOP bin assignment and the spatial subchannel assignment. This distributes the effects of channel estimation errors and localized frequency domain or spatial domain interference so that the decoder error is reduced. It is understood that the bit and power assignments by Information Allocation block 360 take place with knowledge of the post-interleaved channel strength. It is understood that the encoding and decoding process can begin and end within one burst, or it may take place over a multitude of bursts.

One skilled in the art will recognize that a multitude of less sophisticated adaptive power and bit loading algorithms can be advantageously applied to a substantially independent set of space frequency subchannels. One example is an algorithm wherein a space frequency subchannel is either loaded with maximum power or no power and the bit distribution may be adjusted in only two increments.

A second alternative embodiment shown in Fig. 19 includes one encoder for each SOP bin, with the output symbols of each encoder allocated among several spatial subchannels. A third embodiment shown in Fig. 20 involves one encoder for each spatial subchannel, with the output symbols of each encoder distributed among the SOP bins for that spatial subchannel. A fourth embodiment shown in Fig. 21 involves a separate encoder for each available space frequency subchannel.

It will be clear to one skilled in the art that the channel estimation tools taught herein are very useful in improving the accuracy of the channel estimates used for the bit loading and decoding process.

One skilled in the art will recognize that many of the other coding techniques for parallel sub-channel bit loading communication systems, not mentioned here, can also be applied to the present invention.

5 **Space Frequency Trellis Coding with Orthogonal Spatial Subchannels and Flat Power and Bit Distribution**

10 In some cases it is difficult to adaptively load the power and bit assignments for each available space frequency subchannel. For example, the transmitter and receiver may not be able to adapt the loading fast enough to accommodate time domain variation in the channel. In another example, the required feedback from the receiver to the transmitter requires a significant portion of the available reverse link bit rate. Adaptive bit loading may also be overly complicated for certain applications. Thus, it is often advantageous to encode and decode a symbol stream in such a manner that the power and bit allocation is constant for all 15 space frequency subchannels. This is easily accomplished by employing the embodiments depicted in Figs. 22-23, and assigning a constant power and bit allocation to all space frequency subchannels in the Information Allocation block 360.

20 **Space Frequency Coding Without Orthogonal Spatial Subchannels**

In applications where the spatial channels are not processed to achieve substantially orthogonal spatial subchannels within each SOP bin, an advantageous embodiment of the invention involves utilization of a vector maximum likelihood decoder in the receiver to 25 decode a symbol sequence that includes multiple symbols per SOP bin. The vector maximum likelihood detector is capable of determining the transmitted symbol vector in each SOP bin even in the presence of spatial subchannels that contain significant cross-coupling between the channels. The vector maximum likelihood detector uses an estimate of the matrix channel from each SOP bin to decode a sequence of groups of symbols with one group for each SOP bin. The groupings will be referred to here as a multidimensional symbol vector, or simply a 30 symbol vector. The ML detector uses an estimate of the matrix channel that exists in each SOP bin to find the most likely sequence of transmitted encoder vector symbols.

Fig. 24 depicts a transmitter system wherein multiple space/frequency subchannels are employed without spatial orthogonalization. Fig. 25 depicts a receiver system for this application.

35 The bit sequence $b(k)$ is encoded into a sequence of multidimensional symbol vectors in a Bit to Symbol Encoding block 250. Each output of the encoder is an M_0 by 1 complex symbol vector, where M_0 is the number of spatial directions that will be used for transmission. Note that M_0 is preferably chosen to be less than or equal to M_T . A preferable construction of the encoder is a multidimensional trellis encoder. One advantageous metric for designing 40 the trellis encoder constellation and convolutional encoder polynomial will be provided below. Within the previously discussed Symbol Interleaver block 260, the vector symbol sequence is demultiplexed and interleaved with a Symbol Sequence Demultiplexor 300 and a Transmit Symbol Routing block 310. Transmit Symbol Routing block 310 interleaves the vector symbol sequence so that the elements of a given vector symbol are grouped together and transmitted in one SOP bin. Thus, different vectors are separated by a multitude of SOP 45 bins before transmission, but all elements within the vector symbol share the same SOP bin. The purpose of the interleaver is to distribute the vector symbol sequence so that the fading present in the matrix channels within the SOP bins is randomized at the output of the receiver interleaver. The decoder can recover information associated with symbols that are

transmitted through SOP bins that experience a deep fade, provided that the adjacent symbols do not also experience the same fade. Since there is often a high degree of correlation in the fading experienced by adjacent SOP bins, the interleaver makes the fading more random and improves decoder error performance. After interleaving, each element of a vector symbol is
 5 assigned to one antenna for the SOP bin assigned to that vector symbol. Transmitter SOP processors 190 perform the transmitter portion of the SOP.

After the transmitter SOP, it is often advantageous to perform spatial processing with TSP 230. It is understood that the matrix representing the operation of TSP 230, i.e., the Transmitter Weight Matrix, may also be an identity matrix so that no weighting is
 10 implemented. It can be beneficial to choose a number of spatial directions that is less than the number of transmitter antennas. In this case, the Transmitter Weight Matrix increases the dimensionality of the time domain vector sequence from the SOP bank. As an example of when it is advantageous to choose a subset of the available transmitter spatial directions, if the receiver has fewer antennas than the transmitter, then it is known that the information
 15 capacity of the matrix channels within each SOP bin will not support a number of parallel information subchannels that is greater than the number of receive antennas. This implies that the number of symbols in each transmitted symbol vector, and hence the number of transmitted spatial directions, should not be greater than the number of receiver antennas. As another example, in a Rayleigh fading channel, the smallest singular values of an M_R by M_T
 20 matrix channel are on average much weaker than the largest singular value. This implies that the average information capacity contained in the smallest singular value may not justify the extra signal processing complexity required to transmit over that dimension. In both of these cases, it is advisable to choose an advantageous subset of the available transmit spatial directions.

The transmitter may not have knowledge of the individual channel matrices within each SOP bin but may have knowledge of the covariance statistics of the channel matrices, averaged over frequency, or time, or both. In such cases, the Transmitter Weight Matrix can be optimized to select one or more spatial directions that maximize the average received
 30 power for the chosen number of spatial directions. The procedure for optimizing the Transmitter Weight Matrix for this criteria is defined by Equations 50 to 52 and the associated discussion. This is one preferred method of selecting an advantageous set of spatial directions for the Transmitter Weight Matrix. Another advantageous criteria for selecting the transmitter spatial directions is to maximize average received power subject to constraints on the average interference power radiated to unintentional receivers. The
 35 procedure for optimizing the Transmitter Weight matrix for this criterion is defined by Equations 60 and 61 and the associated discussion.

After the time domain signal is spatially processed, the signal is upconverted to the RF carrier frequency using Modulation and RF System 40 before being radiated by Transmit
 40 Antennas 51. Referring now to Fig. 25, at the receiver the signal is downconverted and digitized by Receive Antennas 111 and Demodulation and RF System blocks 120. The RSP 240 may then be used to process the time domain signal. The operation of RSP 240 may be characterized by a Receiver Weight Matrix which may be an identity matrix. One
 45 embodiment involves optimizing the RSP weights to reduce the number of received signals from M_R to M_0 , which is the number of elements in the transmitted symbol vector and is also the number of transmitted spatial directions. In this case, the Receiver Weight Matrix can be optimized to increase the average signal power in each received spatial direction. The optimization procedure to accomplish this is defined by Equations 50 to 53 and the associated text.

Channel ID block 130 is used to estimate the matrix channel in each SOP bin. Procedures for channel estimation are described below. Channel state information for each SOP bin is fed into a Symbol to Bit Detector 280 which decodes the symbol sequence after it is passed through a Symbol Deinterleaver 270.

At the receiver, after de-interleaving the SOP bins, the space-frequency sequence is again converted into a serial symbol stream by Demultiplexor 300. For a given set of spatio-temporal vector symbol sequence possibilities $\{Z\}$, and an estimate, $\hat{H}(n, k)$, of the channel matrix in each SOP bin n at burst k , the maximum likelihood detector is given by equation (70):

$$\{\hat{z}(1)^T, \hat{z}(2)^T, \dots, \hat{z}(N)^T\} = \arg \left\{ \min_{z=\{z(1)^T, z(2)^T, \dots, z(N)^T\}} \sum_{n=1}^N \left\| \mathbf{R}_I(n, k)^{-1/2} (\hat{H}(n, k) \mathbf{z}(n) - \mathbf{x}(n, k)) \right\|_2^2 \right\}$$

where $\mathbf{z}(n)$ is the vector representing the code segment hypothesized for SOP bin n , and $\mathbf{R}_I(n, k)$ is the estimated noise plus interference covariance matrix for SOP bin n and time k . This equation can be solved efficiently using a vector ML detector. The SOP bin channel matrix estimates are understood to include the effects of the Transmitter Weight Matrix and the Receiver Weight Matrix. It is understood that the noise pre-whitening step in the ML detector cost function can be substituted by a bank of RSPs that perform the interference whitening as described herein.

In a Rayleigh fading channel, a desirable metric for designing the trellis code is given by the product of a sum involving the two-norm of vector segments of the trellis code error sequence:

$$\prod_{n=1}^q \|e(n)\|_2^2$$

where q is the number of SOP bins in the error sequence, and $e(n)$ is the vector difference between the true multi-dimensional code symbol segment and the incorrect multi-dimensional symbol code segment for SOP bin n . This code design metric is a generalization on the conventional product distance metric which contains a scalar error entry in the product equation while the new code design metric contains a vector two norm entry in the product equation. It should now be evident that the multidimensional encoder can be realized by either directly producing a vector consisting of a multidimensional QAM symbol with the encoder output or by grouping complex QAM symbols from a one dimensional encoder output into a vector. The vector symbol encoder alternative is preferred in some cases because this approach provides for a larger metric search result and hence a better fading code. After deinterleaving, the decoder that is used at the receiver searches over all possible multidimensional symbols within each SOP bin to maximize Equation 70. It is understood that one skilled in the art will recognize after this discussion that other desirable metrics such as Euclidean distance metrics, metrics designed for Rician fading channels, periodic product distance metrics, and others are straightforward to construct and space-frequency codes can then be determined through well known exhaustive search techniques.

In either the one dimensional encoder case, or the multidimensional encoder case, the encoder constellation selection and code polynomial search to maximize the metric can be carried out using a number of well known procedures.

It is possible to improve the performance of the space-frequency coding system described above by using a number of transmitter antennas, or a number of receiver antennas, that is greater than the number of symbols transmitted in each SOP bin. If the number of receiver antennas is greater than the number of symbols in each SOP bin, then simply applying the approach described above is advantageous. If the number of transmitter antennas is

greater than the number of symbols transmitted in each SOP bin, then the techniques embodied in Equation 70 are advantageous.

Channel Identification

The operation of Channel Identification block and Training Symbol Injection block 20 will now be described. The transceiver should determine the MIMO channel in order to form the TSWs and RSWs. For coherent spatial processing and detection, the receiver should obtain an estimate of the channel. We wish to identify the set of matrix channels that results after processing by the transmitter and receiver portions of an SOP. The notation for this channel is $\mathbf{H}(n) \forall n$ where n is the SOP bin index. Channel identification techniques embodied herein can be applied to several preferable SOP pairs including the IFFT-FFT with cyclic prefix, the multiband filter bank, or any other of a number of well-known SOPs. The following exemplary channel identification approach exploits the correlated frequency fading across and possibly the correlated time fading in the channel. The correlation in the frequency domain arises due to the limited time delay spread of the multipath channel. The correlation in time is due to the fact that the channel, while time-varying, is driven by band-limited Doppler frequencies created by objects, which can include the transmitter and/or receiver, moving in the physical environment.

The wireless link is bidirectional, therefore each end of the link should estimate not only a receive channel, but also a transmit channel. For example, a base station should estimate both an uplink and downlink channel. In systems which employ time division duplexing (TDD), electromagnetic reciprocity implies the receive and transmit propagation environments are the same, allowing the transmit channel to be estimated from the receive channel. However, the transmit and receive electronic responses are not necessarily reciprocal, and because the net channel response includes the electronics, a calibration procedure should be used to account for these differences. This calibration procedure provides for matching in the amplitude and phase response between the multiple transmitter and receiver frequency converters. Several TDD calibration procedures are known in the prior art and will not be discussed herein.

In systems employing frequency division duplexing (FDD), the propagation medium is not reciprocal; however, the paths' angles and average strengths are the same for transmit and receive. This enables the use of subspace reciprocity, but incurs a more rigorous calibration requirement. The FDD calibration should insure subspace reciprocity which requires that the array response vector at a given angle on receive is proportional to the corresponding vector on transmit. This requirement is satisfied by again calibrating the amplitude and phase differences among the multiple transmit and receive frequency converter channels and by matching the transmit and receive antenna element response as well as the array geometry.

An alternative approach to transmit channel estimation in FDD systems uses feedback. The transmit channel is measured by sending training symbols to the receiver, which records the amplitude induced by the training symbols. Using receiver to transmitter feedback on a separate feedback control channel, the training responses are sent back to the transmitter. The transmitter, knowing the training excitations it used and the corresponding responses through feedback, the forward channel can be estimated.

In general, channel identification can be done either with or without training. A desirable channel identification algorithm should be robust to and operate in a variety of modem implementations. A preferable MIMO channel identification technique operates with embedded training inserted into the data stream by Training Symbol Injection block 20 in each burst. In this case, both data symbols and training symbols may be transmitted within a single burst. Furthermore, the channel can be determined in one burst, or filtering training

data gathered over multiple bursts. Being able to update the channel estimates after every received burst makes the overall communication system robust to time variation in the channel. In addition, frequent channel estimates reduce the destructive effects of imperfect carrier frequency recovery. Since imperfect carrier recovery imparts a phase shift to the channel that continues to grow with time, shortening the time between channel estimation events keeps the channel estimation information from becoming “stale”. Note, however, any of the well known blind channel estimation techniques can be used to determine the training symbol outputs as an alternative to using training. However, adaptive blind training is more prone to generating burst errors.

The parameters to be identified are the N MIMO spatial channel matrices. Hence, there are $N \cdot M_R \cdot M_T$ complex elements to be determined,

$$H_{i,j}(n), \quad \forall n \in [1, N], \forall i \in [1, M_R], \forall j \in [1, M_T].$$

By exploiting whatever correlation exists across the SOP bins, it may be possible to reduce the amount of overhead required to identify the channel. The amount of correlation that exists across SOP bins is determined by the specific implementation of the SOP. If the SOP implementation includes the IFFT-FFT pair, and the length of the FIR channel is time limited with $\nu \ll N$, then a relatively large degree of correlation exists across the SOP bins.

In certain embodiments of the invention, the desired technique should identify the MIMO channel on a burst-by-burst basis, such as those with rapidly time-varying channels. This implies that training data should be included in every burst. If the throughput of information is to be maximized, the amount of training data in each burst should be minimized. It is therefore useful to determine the minimum amount of training data required, per burst, that allows full characterization of the channel by the receiver. It turns out that the minimum number of training symbols required to sufficiently excite the MIMO channel for estimation with an OFDM SOP is $M_T \nu$. To understand this result, consider the identification of a SISO channel, where each of the N values of the vector $\mathbf{H}_{i,j}$ should be found. These N values are not independent since,

$$\mathbf{H}_{i,j} = \mathbf{Y} \begin{bmatrix} \mathbf{h} \\ 0 \end{bmatrix} = \mathbf{X} \otimes^{-1} \mathbf{Z},$$

where \mathbf{X} is a vector of all SOP bin outputs for antenna i , \mathbf{Z} is a vector of bin inputs for antenna j , and \mathbf{h} is a vector of the time-domain FIR channel from antenna j to antenna i .

The matrix operator \otimes^{-1} represents element by element divide. Since the time-domain channel is time limited to ν samples, only ν values of the transmitted symbols, \mathbf{Z} , need to be training values. Furthermore, the identification of the SIMO channel only requires the same set of ν transmitted training tones, since each SISO component in the SIMO channel is excited by the same input data. In a system embodiment with multiple inputs ($M_T > 1$), identification of the MIMO channel requires the identification of M_T separate SIMO channels. Hence, only $M_T \nu$ training symbols are needed to sufficiently excite the MIMO channel for channel identification.

MIMO identification

The identification of the MIMO channel is accomplished by separately exciting each of the transmit antennas that will be used for communication. This decomposes the MIMO identification problem into M_T SIMO identification problems. In order to accomplish channel identification in a single burst, M_T mutually exclusive sets of ν bins are selected from the N available bins to carry training symbols. Each transmitter antenna carries training

symbols in a unique one of the M_T sets of bins, while transmitting no energy in the bins contained in the union of the remaining $M_T - 1$ sets of ν bins. This is accomplished by choosing the TSWs 210A-C that correspond to training bins such that a single entry in the vector is “1” and the remaining entries equal to “0”. It is the j^{th} entry of a TSW that is set equal to “1” for those training symbols which are to be transmitted from the j^{th} antenna. For example, say that symbol bin $n = 2$ is one of the training bins associated with transmit antenna 3. Then,

$$\text{TSW}(2,1) = [0 \ 0 \ 1 \ 0 \ \dots \ 0]^T, \text{ and } \text{TSW}(2,m) = 0 \text{ for } \forall m \neq 1,$$

and the corresponding training symbol $z(2,1)$. By examining the contents of each set of training bins separately, the MIMO channel response is determined by finding M_T independent SIMO channel responses.

In embodiments in which rapid updates of the channel estimate is not required, another exemplary training scheme may be employed. This training scheme involves using just one set of ν training bins. On a given burst, one of the transmit antennas sends training symbols in the training bins and the other antennas transmit no energy in those bins. This allows the receiver to identify one of the M_T SIMO channels. On the next burst, a different antenna sends training symbols in the training bins while the other antennas transmit no energy in those same bins. The receiver is then able to identify another set of N SIMO channels. This procedure is repeated until training data has been sent by each of the transmit antennas, allowing the entire MIMO channel to be identified. The entire procedure is repeated continuously so that full channel is determined every M_T bursts.

SIMO channel identification

We have just shown that identification of the MIMO channel can be accomplished by successive identification of each SIMO channel. It is therefore useful to discuss specific techniques for obtaining a SIMO channel response. The following discussion assumes that the SOP is the IFFT-FFT pair. Channel identification techniques for other SOPs that exploit frequency and possibly time correlation in the similar fashion will be obvious to one skilled in the art.

It is assumed that a certain subset of available SOP bins are allocated for training. Let J be this set of frequency bins used for learning a SIMO channel. To begin, assume that J contains ν bin indices. Furthermore, let \mathbf{Z}_i be the ν training symbols and $\mathbf{X}_{t,i}$ be the received data in the training frequency-bins from antenna i . Let the quantities $\hat{\mathbf{h}}_i, \hat{\mathbf{H}}_i$ be the estimated time-domain and frequency-domain channels from the transmit antenna under consideration to the receive antenna i . In other words, $\hat{\mathbf{h}}_i$ is the ν -length impulse response from the input under consideration to output i . Likewise, $\hat{\mathbf{H}}_i$ is a vector of N frequency domain values for this channel. With these definitions, it can be shown that

$$\hat{\mathbf{h}}_i = \mathbf{Y}_{J,\bar{\nu}}^{-1} (\mathbf{X}_{t,i} \otimes^{-1} \mathbf{Z}_i), \quad (81)$$

and

$$\hat{\mathbf{H}}_i = \mathbf{Y}_{N,\bar{\nu}} \hat{\mathbf{h}}_i. \quad (82)$$

where,

$$\bar{\nu} = \{1, 2, \dots, \nu\},$$

$$\bar{N} = \{1, 2, \dots, N\},$$

and

$$\mathbf{Y}_{pQ} = \frac{1}{\sqrt{N}} e^{-j2\pi pq/N}, \quad \forall p \in \{P\}, \quad \forall q \in \{Q\}.$$

- 5 This also generalizes to any number of training tones, γ , in which case the set J includes γ bin indices. When $\gamma \geq \nu$, the frequency domain channel can be determined by,

$$\hat{\mathbf{H}}_i = \mathbf{Y}_{\bar{N}, \nu} (\mathbf{Y}_{J, \nu}^H \mathbf{Y}_{J, \nu})^{-1} \mathbf{Y}_{J, \nu}^H (\mathbf{X}_{t,i} \otimes^{-1} \mathbf{Z}_t). \quad (83)$$

Note that many of the above calculations can be performed in advance if the training bins are predetermined and fixed. Then, the matrix $\mathbf{Y}_{\bar{N}, \nu} (\mathbf{Y}_{J, \nu}^H \mathbf{Y}_{J, \nu})^{-1} \mathbf{Y}_{J, \nu}^H$ can be computed and
10 stored.

Note that there is no requirement that the training symbols always reside in the same bins from burst to burst. As long as the transmitter and receiver both know where the training symbols are placed in any given burst, the training bins may be varied from one burst to the next. This may be useful to characterize the nature of colored (across SOP bins) noise and/or interference are present.
15

A highly advantageous simplification of (83) can be done when ν training symbols are placed in bins that are evenly spaced throughout the burst. In other words, $J = \{0, \frac{N}{\nu}, \frac{2N}{\nu}, \dots, \frac{(\nu-1)N}{\nu}\}$. In this case, $\mathbf{Y}_{J, \nu}^{-1}$ is equal to the ν -point IFFT matrix so that equation (81) represents the execution of an ν -point IFFT. One may then obtain $\hat{\mathbf{H}}_i$ in
20 equation (82) by performing an N -point FFT on a vector consisting of $\hat{\mathbf{h}}_i$ padded with $N - \nu$ zeros. This approach to identifying $\hat{\mathbf{H}}_i$ is only of computation order $(N + \nu) \log_2 \nu$.

Identification over multiple bursts

- Identification accuracy can be improved by either increasing the number of training
25 symbols within each burst or by averaging over multiple bursts if the channel is correlated from one burst to another. Some degree of time domain correlation exists in the channel because the Doppler frequency shifts caused by moving objects in the physical environment are band-limited. This time correlation can be exploited by recursively filtering the estimated channel from the present burst with channel estimates from previous bursts. A general
30 filtering approach is represented by

$$\tilde{\mathbf{h}}(k+1) = \mathbf{F}(k) \tilde{\mathbf{h}}(k) + \mathbf{G}(k) \hat{\mathbf{h}}(k)$$

- where $\tilde{\mathbf{h}}$ is the smoothed channel estimate of $\hat{\mathbf{h}}$ over bursts k . The particular recursive filter weights $\mathbf{F}(k)$ and $\mathbf{G}(k)$ can be derived in a number of fashions. Two exemplary filtering
35 methods are given in the following. The first approach determines a time-invariant FIR filter for each element of \mathbf{h} based on a MMSE cost function. The second design is time-varying Kalman filter.

- A particularly simple, yet effective, filter design technique is the determination of a time-invariant FIR filter, \mathbf{w} , that minimizes the MMSE between the true channel impulse
40 response and the filtered estimate. This design approach is referred to as Wiener filtering. In this embodiment, independent fading is assumed on each element of the channel impulse response. Therefore, each element of \mathbf{h} can be considered independently. An FIR filter produces a filtered estimate by forming a weighted sum of the previous $p+1$ estimates for that particular impulse response element,

$$\tilde{h}_i(k) = \mathbf{w}^H \begin{bmatrix} \hat{h}_i(k) \\ \vdots \\ \hat{h}_i(k-p) \end{bmatrix}, \quad \forall i = 1, 2, \dots, \nu.$$

Using ν such identical filters for each element of the impulse response, then the filtered estimate is given by $\tilde{\mathbf{h}}(k) = [\tilde{h}_1(k) \ \dots \ \tilde{h}_\nu(k)]^T$. The Wiener filter solution for \mathbf{w} satisfies the following equation,

$$\min_{\mathbf{w}} E \left(\left| \mathbf{w}^H \tilde{\mathbf{h}}_i(k) - h_i(k) \right|^2 \right) = \min_{\mathbf{w}} E \left(\left| \mathbf{w}^H \begin{bmatrix} \hat{h}_i(k) \\ \vdots \\ \hat{h}_i(k-p) \end{bmatrix} - h_i(k) \right|^2 \right).$$

The solution for the above optimization problem is given by,

$$\mathbf{w} = \left[E(\tilde{\mathbf{h}}_i(k) \tilde{\mathbf{h}}_i(k)^H) \right]^{-1} E[\tilde{\mathbf{h}}_i(k) h_i(k)] = \mathbf{R}_{\tilde{\mathbf{h}}_i}^{-1} \mathbf{R}_{\tilde{\mathbf{h}}_i h_i}.$$

If each delay in the channel impulse response undergoes Raleigh fading is assumed then,

$$\mathbf{R}_{\tilde{\mathbf{h}}_i} = \sigma_h^2 \begin{bmatrix} J_0(0) & J_0(\omega(N+\nu)T) & \dots & J_0(\omega(N+\nu)T) \\ J_0(\omega(N+\nu)T) & \ddots & & \vdots \\ \vdots & & \ddots & \\ J_0(\omega p(N+\nu)T) & \dots & & J_0(0) \end{bmatrix} + \sigma_e^2 \mathbf{I}$$

and

$$\mathbf{R}_{\tilde{\mathbf{h}}_i h_i} = \sigma_h^2 \begin{bmatrix} J_0(0) \\ J_0(\omega(N+\nu)T) \\ \vdots \\ J_0(\omega p(N+\nu)T) \end{bmatrix},$$

where T is the sampling rate, ω is the maximum Doppler frequency, and J_0 is the zeroth-order Bessel function. The quantities σ_h^2 and σ_e^2 are the average channel power and the channel estimation noise power, respectively.

This filtering approach has many advantages. First, it is computationally simple. Each coefficient of the channel impulse response is filtered independently with a constant, precomputed FIR weighting. Second, the underlying time-correlation in the multipath fading channel is efficiently exploited. Third, the exact values used for the filter are optimal in a MMSE sense.

A more generalized time-varying filtering approach is now developed based on the Kalman filtering equations. A general model for the time-correlated nature of the channel impulse response is given by the following set of equations,

$$\mathbf{f}(k+1) = \mathbf{A}\mathbf{f}(k) + \mathbf{q}(k)$$

$$\tilde{\mathbf{h}}(k) = \mathbf{C}\mathbf{f}(k) + \mathbf{r}(k)$$

where the \mathbf{q} and \mathbf{r} represent noises with covariances \mathbf{Q} and \mathbf{R} , respectively. The matrices $\mathbf{A}, \mathbf{C}, \mathbf{Q}, \mathbf{R}$ are used to define the particular model for the correlation of the impulse response

over bursts. Note that the vector $\tilde{\mathbf{h}}$ can also include the impulse response coefficients for more than one receive antenna. In this case, the above model can include both time correlation and correlation across space.

In a multi-access scheme, successive channel identifications may occur at an irregular rate. In this case, this Kalman filter approach is particularly useful since the filtering can be done with measurement updates and time updates,

$$\begin{aligned}\hat{\mathbf{f}}(k+1) &= \mathbf{A}(\mathbf{I} - \mathbf{L}(k)\mathbf{C})\hat{\mathbf{f}}(k) + \mathbf{A}\mathbf{L}(k)\hat{\mathbf{h}}(k) \\ \mathbf{L}(k) &= \hat{\mathbf{P}}(k)\mathbf{C}^H (\mathbf{C}\hat{\mathbf{P}}(k)\mathbf{C}^H + \mathbf{R})^{-1} \\ \hat{\mathbf{P}}(k) &= \mathbf{A}(\mathbf{I} - \mathbf{L}(k)\mathbf{C})\hat{\mathbf{P}}(k)\mathbf{A}^H + \mathbf{Q} \\ \tilde{\mathbf{h}}(k) &= \mathbf{C}\hat{\mathbf{f}}(k)\end{aligned}$$

where $\mathbf{L}(k) = \mathbf{0}$ when the receiver is not receiving data in the present burst.

Interference Subspace Identification

For many of the spatial processing techniques embodied in this invention, the operation of the TSP and RSP can depend, in part, on the level of interference present in the wireless environment within which the invention operates. More specifically, it may be preferable to reduce the amount of interference contributed to other receivers by a judicious choice of the TSWs. It may also be preferable to improve the signal quality at the receiver by using RSWs that reject interference. In these cases, some quantitative measure of the interference across space and frequency is needed.

One preferable measure of the interference present is the so-called interference spatial covariance matrix, which describes interference correlation across space for each frequency bin,

$$\mathbf{R}_I(n) = E[\mathbf{I}(n)\mathbf{I}(n)^H], \quad (1)$$

where $\mathbf{x}_I(n)$ represents an M_R -length received vector of signals from the interfering transmitter(s). To be more precise, $\mathbf{R}_I(n)$ describes the interference *and noise* correlation across space for each frequency bin. Since we assume that the noise at the output of each receiver antenna path is additive thermal noise, and therefore that the additive noise is uncorrelated between any two antenna outputs, the noise contribution to $\mathbf{R}_I(n)$ is non-zero only on the matrix diagonal. In environments dominated by interference, i.e. the interference power at the receiver is much stronger than the additive receiver noise, the noise contribution to $\mathbf{R}_I(n)$ can be neglected. The interference covariance matrix contains information about the average spatial behavior of the interference. The eigenvectors of this matrix define the average spatial directions (in M_R -space) occupied by the interference. The eigenvalues of the matrix indicate the average power occupied by the interference in each the eigendirection. The eigendirections that are associated with large eigenvalues indicate spatial directions that receive a large amount of average interference power. The eigendirections associated with small eigenvalues indicate spatial directions that are preferable in that they receive less average interference power.

Identifying the receive covariance matrix, $\mathbf{R}_I(n)$, is required for finding preferable RSPs. An analogous transmit covariance matrix is required for finding preferable TSPs. Notice that we've defined $\mathbf{R}_I(n)$ in terms of received signal samples in Equation (1). Since the received signal samples are not usually available at the transmitter, it is preferable to

derive the transmit covariance matrix from the receive covariance matrix. In time division duplex (TDD) systems, the receive and transmit covariance matrices are substantially equal when the time between reception and transmission is short relative to the rate of time variation in the channel. In frequency division duplex (FDD) systems, the transmit and receive channel values are generally not correlated with one another at any given instant in time. However, the transmit and receive covariance matrices are substantially equal in FDD systems when sufficient time averaging is used in the calculation of \mathbf{R}_I . There are many techniques for determining the interference covariance matrix, two of which are discussed below.

One interference characterization approach simply averages the received antenna signals during time periods in which the desired transceiver is not transmitting information. Since there is no desired signal arriving at the receiver, the interference (and noise) covariance is precisely equal to the measured sample covariance matrix,

$$\hat{\mathbf{R}}_I(n) = \hat{\mathbf{R}}_x(n) = \frac{1}{k_2 - k_1} \sum_{j=k_1}^{k_2} \mathbf{x}(n, j) \mathbf{x}(n, j)^H.$$

In TDD systems, one can make use of “dead-time” to collect samples from the receiver during which time no energy from the transmitting end arrives at the receiver. The “dead-time” is approximately equal to the round trip propagation delay between the two ends of the wireless communications link, and occurs when a transceiver switches from transmission mode to reception mode. In the above equation, k_1 and k_2 are the burst indexes corresponding to the first and last bursts received during the dead time. Thus, the interference covariance can be estimated with no increase in overhead.

The interference covariance matrices can also be determined while the desired signal is being transmitted to the receiver. One approach involves first determining the interference signal and subsequently finding the interference signal covariance. The estimated received interference is formed by subtracting the estimated desired signal from the total received signal,

$$\hat{\mathbf{I}}(n, k) = \mathbf{x}(n, k) - \hat{\mathbf{H}}(n, k) \hat{\mathbf{z}}(n, k).$$

Therefore, once the channel is identified and the information symbols determined, the remaining signal is considered to be interference. The interference covariance matrix for bin n , averaged over K bursts is given by,

$$\mathbf{R}_I(n, k) = \frac{1}{K} \sum_{j=k-K+1}^k \hat{\mathbf{I}}(n, k) \hat{\mathbf{I}}(n, k)^H.$$

It is understood that when estimating the covariance matrix, it may be desirable to filter the covariance matrix estimates. It may also be advantageous in certain embodiments to determine an average interference covariance matrix across SOP bins. For example, within a multiple access system bursts may only be received occasionally, making it difficult to acquire a sufficient number of bursts with which to form an accurate covariance matrix for each bin. So instead of averaging over time (a series of received bursts), a covariance matrix is formed by averaging over the SOP bins of a single burst,

$$\mathbf{R}_I(k) = \frac{1}{N} \sum_{n=1}^N \hat{\mathbf{I}}(n, k) \hat{\mathbf{I}}(n, k)^H.$$

It may also be preferable to estimate the interference covariance matrices in an alternate frequency band. This can be done using the “dead-time” approach given above. This may be advantageous when the transceiver has the capability of choosing alternate frequency bands for communicating. Estimates of interference in alternate bands provides the foundation for an adaptive frequency hopped scheme.

- It is understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application and scope of the appended claims and their full scope of equivalents. For
- 5 example, much of the above discussion concerns signal processing in the context of a wireless communication system where multiple inputs or multiple outputs are accessed by multiple transmitter antenna elements or multiple receiver antenna elements. However, the present invention is also useful in the context of wireline channels accessible via multiple inputs or multiple outputs.

WHAT IS CLAIMED IS:

1. In a digital communication system, a method for communicating comprising the steps of:

transmitting signals from one or more transmitter antenna elements;

receiving said signals from via a plurality of receiver antenna elements;

wherein separation of radiation patterns among either said transmitter antenna elements or said receiver antenna elements is insufficient to establish completely isolated spatial directions for communication; and wherein

at least one of said transmitting and receiving steps comprises processing said signals to increase isolation between spatial directions employed for communication at a common frequency.

2. The method of claim 1 wherein a channel coupling said plurality of transmitter antenna elements and receiver antenna elements at said common frequency is characterized by a spatial channel matrix having a rank greater than one.

3. In a digital communication system, a method for communicating comprising the steps of:

transmitting signals from one or more transmitter antenna elements;

receiving said signals via a plurality of receiver antenna elements;

wherein separation of radiation patterns among either said transmitter antenna elements or said receiver antenna elements is insufficient to establish completely isolated spatial directions for communication; and wherein

at least one of said transmitting and receiving steps comprises processing said signals to increase isolation between subchannels, each subchannel associated with a spatial direction and a bin of a substantially orthogonalizing procedure.

4. The method of claim 3 wherein said substantially orthogonalizing procedure belongs to a group including: an inverse Fast Fourier Transform, a Fast Fourier Transform, a Hilbert transform, a wavelet transform, and processing through a set of bandpass filter/frequency upconverter pairs operating at spaced apart frequencies..

32
33 5. In a digital communication system, a method for preparing a sequence of
34 symbols for transmission via a plurality of inputs of a channel:

35 a) inputting said symbols of said sequence into a plurality of inputs
36 corresponding to a plurality of subchannels of said channel, each subchannel corresponding to
37 an input bin of a transmitter substantially orthogonalizing procedure and a spatial direction;

38 b) for each input bin, spatially processing symbols inputted to said subchannels
39 corresponding to said input bin, to develop a spatially processed symbol to assign to each
40 combination of channel input and input bin of said transmitter substantially orthogonalizing
41 procedure; and

42 c) applying, independently for each said channel input, said transmitter
43 substantially orthogonalizing procedure to said spatially processed symbols assigned to each
44 said channel input.

45
46 6. The method of claim 5 wherein said b) step has the effect of making
47 spatial directions of said subchannels into a set of orthogonal spatial dimensions.

48
49 7. The method of claim 5 wherein said transmitter substantially
50 orthogonalizing procedure belongs to one of a group consisting of an inverse Fast Fourier
51 Transform, a Fast Fourier Transform, a discrete cosine transform, a Hilbert transform, a
52 wavelet transform, and processing through a plurality of bandpass filter/frequency converter
53 pairs centered at spaced apart frequencies.

54
55 8. The method of claim 5 further comprising the step of, after said c) step,
56 applying a cyclic prefix processing procedure to a result of said substantially orthogonalizing
57 procedure independently for each channel input.

58
59 9. The method of claim 5 wherein said transmitter substantially
60 orthogonalizing procedure is optimized to reduce interference to unintended receivers.

61

62 10. The method of claim 5 wherein said b) step comprises, for each
63 particular input bin, multiplying a vector comprising symbols allocated to subchannels
64 corresponding to said input bin by a beneficial weighting matrix, elements of a result vector of
65 said multiplying step corresponding to different channel inputs of said plurality of channel
66 inputs.

67
68 11. The method of claim 10 wherein said beneficial weighting matrix
69 comprises an input singular matrix of a matrix containing values representing characteristics of
70 said channel, said coupling said plurality of channel inputs to one or more channel outputs.

71
72 12. The method of claim 10 wherein said beneficial weighting matrix is
73 obtained from a matrix containing values representing characteristics of a channel coupling
74 said plurality of channel inputs to one or more channel outputs.

75
76 13. The method of claim 10 wherein said beneficial weighting matrix is
77 chosen to reduce interference to unintended receivers.

78
79 14. The method of claim 13 wherein said beneficial weighting matrix is
80 chosen based upon characterization of a desired signal subspace.

81
82 15. The method of claim 14 wherein said beneficial weighting matrix is
83 chosen further based upon characterization of an undesired signal subspace.

84
85 16. The method of claim 15 wherein characterizations of said desired signal
86 subspace and said undesired signal subspace are averaged over at least one of time and
87 frequency.

88
89 17. The method of claim 10 wherein said b) step comprises performing said
90 spatial processing step so as to reduce interference radiated to unintended receivers.

91 18. The method of claim 10 wherein said b) step comprises, for each input
92 bin, allocating symbols to each combination of channel input and input bin so that there

is a one-to-one mapping between spatial direction of a particular subchannel to which a particular symbol has been allocated and channel input to which said particular symbol is allocated.

19. The method of claim 10 further comprising the step of prior to said b) step applying a coding procedure to said symbols.

20. The method of claim 19 wherein said coding procedure is applied independently for each of said subchannels.

21. The method of claim 19 wherein said coding procedure is applied independently for each group of subchannels corresponding to an input bin of said substantially orthogonalizing procedure.

22. The method of claim 19 wherein said coding procedure is applied independently for each group of subchannels corresponding to a particular spatial direction.

23. The method of claim 19 wherein said coding procedure is applied integrally across all of said subchannels.

24. The method of claim 19 wherein said coding procedure belongs to a group consisting of: convolutional coding, Reed-Solomon coding, CRC coding, block coding, trellis coding, turbo coding, and interleaving.

25. The method of claim 19 wherein said coding procedure comprises a trellis coding procedure.

26. The method of claim 25 wherein a code design of said trellis coding procedure is based on one of: improved bit error performance in interference channels, a periodic product distance metric, exhaustive code polynomial search for favorable bit error rate polynomial searches, combined weighting of product distance and Euclidean distance,

product distance of multiple Euclidean distances over short code segments or over a multi-dimensional symbol, and sum of product distances over short code segments.

27. The method of claim 25 wherein a code design of said trellis coding procedure is optimized for performance in a fading matrix channel.

28. The method of claim 19 wherein said coding procedure comprises a one-dimensional trellis coding procedure followed by an interleaving procedure with sequential groups of symbols output by said trellis coding having their internal order maintained by said interleaving procedure.

29. The method of claim 19 wherein said coding procedure comprises a multi-dimensional trellis coding procedure followed by an interleaving procedure with groups of one-dimensional symbols output simultaneously by said multi-dimensional trellis coding procedure having their internal order maintained by said interleaving procedure.

30. The method of claim 10 wherein bit loading and power are allocated to each subchannel.

31. The method of claim 10 further comprising the step of retransmitting symbols by repeating at least one of said a), b), and c) steps upon receipt of a notification that said symbols to be retransmitted have been incorrectly received.

32. The method of claim 10 wherein said channel comprises a wireless channel and said plurality of channel inputs are associated with a corresponding plurality of transmitter antenna elements

33. The method of claim 32 wherein said plurality of transmitter antenna elements are co-located.

154 34. The method of claim 32 wherein said plurality of transmitters are at
155 disparate locations.
156

157 35. A method of processing a sequence of symbols received via a plurality of
158 outputs of a channel, said method comprising the steps of:

159 a) applying a receiver substantially orthogonalizing procedure to said sequence
160 of symbols, said procedure being applied independently for each of said plurality of channel
161 outputs, each output symbol of said receiver substantially orthogonalizing procedure
162 corresponding to a particular output bin and a particular one of said channel outputs; and

163 b) for each output bin, spatially processing symbols corresponding to said
164 output bin to develop spatially processed symbols assigned to a plurality of spatial directions,
165 each combination of spatial direction and output bin specifying one of a plurality of
166 subchannels.
167

168 36. The method of claim 35 wherein said b) step has the effect of making
169 said plurality of spatial directions into a set of orthogonal spatial dimensions.
170

171 37. The method of claim 35 wherein said receiver substantially
172 orthogonalizing procedure belongs to one of a group consisting of an inverse Fast Fourier
173 Transform, a Fast Fourier Transform, a discrete cosine transform, a Hilbert transform, a
174 wavelet transform, and processing through a plurality of bandpass filter/frequency converter
175 pairs centered at spaced apart frequencies.
176

177 38. The method of claim 35 further comprising the step of, prior to said a)
178 step, applying a cyclic prefix removal procedure to said sequence of symbols independently
179 for each of said channel outputs.
180

181 39. The method of claim 35 wherein said receiver substantially
182 orthogonalizing procedure is optimized to reduce deleterious effects of interference from
183 undesired co-channel transmitters.
184

185 40. The method of claim 35 wherein said b) step comprises, for each
186 particular output bin, multiplying a vector comprising symbols of said output bin by a
187 beneficial weighting matrix, elements of a result vector of said multiplying step corresponding
188 to different spatial directions.

189
190 41. The method of claim 40 wherein said beneficial weighting matrix
191 comprises an output singular vector of a matrix containing values representing characteristics
192 of said channel, said channel coupling one or more channel inputs to said plurality of channel
193 outputs.

194
195 42. The method of claim 40 wherein said beneficial weighting matrix is
196 chosen to minimize deleterious effects of interference from undesired transmitters.

197
198 43. The method of claim 42 wherein said beneficial weighting matrix is
199 chosen based upon characterization of a desired signal subspace.

200
201 44. The method of claim 43 wherein said beneficial weighting matrix is
202 chosen further based upon characterization of an undesired signal subspace.

203
204 45. The method of claim 44 wherein said characterizations of said desired
205 signal subspace and said undesired signal subspace are averaged over at least one of time and
206 frequency.

207
208 46. The method of claim 40 wherein said beneficial weighting matrix is
209 obtained from a matrix containing values representing characteristics of said channel, said
210 channel coupling one or more channel inputs and said plurality of channel outputs.

211
212 47. The method of claim 46 wherein said beneficial weighting matrix is
213 obtained by an MMSE procedure.

214

215 48. The method of claim 35 further comprising the step of after said b) step
216 applying a decoding procedure to said symbols.

217
218 49. The method of claim 48 wherein said decoding procedure is applied
219 independently for each of said plurality of subchannels.

220
221 50. The method of claim 48 wherein said decoding procedure is applied
222 independently for each group of subchannels corresponding to an output bin of said
223 substantially orthogonalizing procedure.

224
225 51. The method of claim 48 wherein said decoding procedure is applied
226 independently for each group of subchannels corresponding to a spatial direction.

227
228 52. The method of claim 48 wherein said decoding procedure is applied
229 integrally across all of said plurality of subchannels.

230
231 53. The method of claim 48 wherein said decoding procedure belongs to a
232 group consisting of: Reed-Solomon decoding, CRC decoding, block decoding, and de-
233 interleaving.

234
235 54. The method of claim 48 wherein said decoding procedure comprises a
236 code sequence detection procedure to decode a trellis code, or convolutional code.

237
238 55. The method of claim 54 wherein said code sequence detection procedure
239 employs a metric belonging to a group consisting of: Euclidean metric, weighted Euclidean
240 metric, and Hamming metric.

241
242 56. The method of claim 48 wherein said decoding procedure reduces
243 deleterious effects of interference from undesired transmitters.

244
245 57. The method of claim 35 further comprising the step of:

246 sending a retransmission request when received symbols are

247 determined to include errors.

248
249 58. The method of claim 35 wherein said channel comprises a wireless
250 channel and said plurality of channel outputs are coupled to a plurality of corresponding
251 receiver antenna elements.

252
253 59. The method of claim 35 wherein said plurality of receiver antenna
254 elements are co-located.

255
256 60. The method of claim 35 wherein said plurality of receiver antenna
257 elements are at disparate locations.

258
259 61. In a digital communication system, a method for preparing a sequence of
260 symbols for transmission via a plurality of inputs to a channel, said method comprising the
261 steps of:

262 selecting a weighting vector for optimal transmission;

263 applying a transmitter substantially orthogonalizing procedure to
264 said sequence of symbols to develop a time domain symbol sequence; and

265 multiplying at least one symbol of said time domain symbol
266 sequence by said weighting vector to develop a result vector, elements of said result vector
267 corresponding to symbols to be transmitted via individual ones of said plurality of channel
268 inputs.

269
270 62. The method of claim 61 wherein said weighting vector comprises an
271 element indicating delay to be applied for a particular one of said plurality of channel inputs.

272
273 63. The method of claim 61 wherein said weighting vector is optimized to
274 reduce interference to unintended receivers.

275

276 64. The method of claim 61 wherein said weighting vector is chosen based
277 upon characterization of a desired signal subspace.

278

279 65. The method of claim 64 wherein said weighting vector is chosen further
280 based upon characterization of an undesired signal subspace.

281

282 66. The method of claim 65 wherein said characterizations of said desired
283 signal subspace and said undesired signal subspace are averaged over at least one of time and
284 frequency.

285

286 67. The method of claim 61 wherein said channel comprises a wireless
287 channel and said plurality of channel inputs are associated with a plurality of transmitter
288 antenna elements.

289

290

291

292 68. In a digital communication system, a method for processing a plurality
293 of symbols received via a plurality of outputs of a channel, said method comprising the steps
294 of:

295 selecting a weighting vector for optimal reception;
296 multiplying an input vector whose elements correspond to
297 symbols received substantially simultaneously via a selected one of said plurality of channel
298 outputs by said weighting vector to obtain a time domain symbol corresponding to a particular
299 input bin of a receiver substantially orthogonalizing procedure;
300 repeating said multiplying step for successive received symbols to
301 obtain time domain symbols corresponding to successive input bins of said receiver
302 substantially orthogonalizing procedure; and
303 applying said receiver substantially orthogonalizing procedure to
304 said obtained time domain symbols.

305
306 69. The method of claim 68 wherein said weighting vector comprises an
307 element indicating delay to be applied for a particular one of said plurality of channel outputs.
308

309 70. The method of claim 68 wherein said weighting vector is optimized to
310 reduce deleterious effects of interference from unintended transmitters.
311

312 71. The method of claim 68 wherein said weighting vector is chosen based
313 upon characterization of a desired signal subspace.
314

315 72. The method of claim 71 wherein said weighting vector is chosen further
316 based upon characterization of an undesired signal subspace.
317

318 73. The method of claim 72 wherein said characterizations of said desired
319 signal subspace and said undesired signal subspace are averaged over at least one of frequency
320 and time.
321

74. The method of claim 71 wherein said channel comprises a wireless channel and said plurality of channel outputs are associated with a plurality of corresponding receiver antenna elements.

75. In a digital communication system, a method of preparing symbols for transmission via a plurality of inputs of a channel, said method comprising the steps of:

directing symbols to input bins of a transmitter substantially orthogonalizing procedure so that each input bin has an allocated symbol;

for each particular input bin, spatially processing said symbol allocated to said particular input bin to develop a spatially processed symbol vector, each element of said spatially processed symbol vector being assigned to one of said channel inputs;

applying said transmitter substantially orthogonalizing procedure for a particular channel input, inputs to said substantially orthogonalizing procedure being for each input bin, a symbol of said processed symbol vector for said input bin corresponding to said particular channel input; and

repeating said applying step for each of said plurality of channel inputs.

76. The method of claim 75 further comprising the step of:

applying a cyclic prefix processing procedure to outputs of said substantially orthogonalizing procedure independently for each particular channel input.

77. The method of claim 75 wherein said transmitter substantially orthogonalizing procedure is optimized to reduce interference to unintended receivers.

78. The method of claim 75 wherein said processing step comprises:

multiplying said symbol allocated to said particular input bin by a beneficial weighting vector to obtain said spatially processed symbol vector.

352 79. The method of claim 78 wherein said beneficial weighting vector is an
353 input singular vector of a matrix storing values indicative of said channel, said channel
354 coupling said plurality of channel inputs and one or more channel outputs.
355

356 80. The method of claim 78 wherein said beneficial weighting vector is
357 chosen to select a beneficial spatial direction for transmission.
358

359 81. The method of claim 80 wherein said beneficial weighting vector is
360 chosen to reduce interference to unintended receivers.
361

362 82. The method of claim 81 wherein said beneficial weighting vector is
363 chosen based upon characterization of a desired signal subspace
364

365 83. The method of claim 82 wherein said beneficial weighting vector is
366 chosen further based upon characterization of an undesired signal subspace.
367

368 84. The method of claim 83 wherein said characterizations of said desired
369 signal subspace and said undesired signal subspace are averaged over at least one of time and
370 frequency.
371

372 85. The method of claim 75 wherein said channel comprises a wireless
373 channel and said plurality of channel inputs are associated with a corresponding plurality of
374 transmitter antenna elements.
375

376 86. In a digital communication system, a method for processing symbols
377 received by a plurality of outputs of a channel comprising the step of:

378 applying a receiver substantially orthogonalizing procedure to symbols received
379 via a particular one of said channel outputs;

380 repeating said applying step for each of said channel outputs to develop a result
381 vector for each of a plurality of output bins of said receiver substantially orthogonalizing
382 procedure, said result vector including a result symbol for each of said channel outputs; and

for each particular output bin of said receiver substantially orthogonalizing procedure, spatially processing said result vector for said particular output bin to develop a spatially processed result symbol for said particular output bin.

87. The method of claim 86 further comprising the step of:
prior to said applying step, applying a cyclic prefix removal procedure to symbols independently for each of said channel outputs.

88. The method of claim 86 wherein said substantially orthogonalizing procedure is optimized to reduce deleterious effects of interference from unintended transmitters.

89. The method of claim 86 wherein said spatially processing step comprises multiplying a beneficial weighting vector by said result vector to obtain said spatially processed result symbol.

90. The method of claim 88 wherein said beneficial weighting vector is an input singular vector of a matrix storing values indicative of characteristics of said channel, said channel coupling one or more channel inputs and said plurality of channel outputs.

91. The method of claim 88 wherein said beneficial weighting vector is chosen to select a particular spatial direction for reception.

92. The method of claim 91 wherein said beneficial weighting vector is chosen to minimize deleterious effects of interference from unintended transmitters.

93. The method of claim 91 wherein said beneficial weighting vector is chosen based upon characterization of a desired signal subspace.

94. The method of claim 93 wherein said beneficial weighting vector is chosen based upon characterization of an undesired signal subspace.

95. The method of claim 94 wherein said characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of time and frequency.

96. The method of claim 86 wherein said channel comprises a wireless channel and said plurality of channel outputs are associated with a corresponding plurality of channel outputs.

97. In a digital communication system including a communication channel having one or more inputs and at least one or more outputs, a method for determining characteristics of said channel based on signals received by said one or more outputs, comprising the steps of:

a) receiving via said one or more channel outputs, at least ν training symbols transmitted via a particular spatial direction of said channel, ν being an extent in symbol periods of a duration of significant terms of an impulse response of a channel; and

b) applying a substantially orthogonalizing procedure to said received at least ν training symbols to obtain a time domain response for said spatial direction; and

c) applying an inverse of said substantially orthogonalizing procedure to a zero-padded version of said time domain response to obtain a frequency response for said particular spatial direction.

98. The method of claim 97 wherein said substantially orthogonalizing procedure comprises an inverse Fast Fourier Transform and said inverse of said substantially orthogonalizing procedure comprises a Fast Fourier Transform.

99. The method of claim 98 wherein said a) step comprises receiving exactly ν training symbols.

100. The method of claim 97 further comprising the step of repeating said a), b), c), and d) steps for a plurality of spatial directions.

101. The method of claim 99 wherein each of said plurality of spatial directions corresponds to transmission through one of said plurality of channel inputs exclusively.

102. The method of claim 98 wherein said v training symbols belong to a burst of N symbols and said characteristics are determined for said burst.

103. The method of claim 102 further comprising the steps of repeating said a), b), c), and d) steps for successive bursts.

104. The method of claim 103 further comprising the step of after, said b) step, smoothing said time-domain response over successive bursts.

105. The method of claim 104 wherein said smoothing step comprises Kalman filtering.

106. The method of claim 104 wherein said smoothing step comprises Wiener filtering.

107. The method of claim 97 wherein said communication channel comprises known and unknown components, wherein said effects of said known components are removed by deconvolution, and characteristics of said unknown components are determined by said a), b), c), and d) steps, thereby reducing .

108. In a digital communication system including a communication channel having one or more inputs and one or more outputs, a method for determining characteristics of said channel based on signals received via one or more channel outputs, comprising the steps of:

receiving training symbols via said channel outputs; and

475 computing characteristics of said channel based on said received
476 training symbols and assumptions that an impulse response of said channel is substantially
477 time-limited and that variation of said impulse response over time is continuous.

478
479 109. In a digital communication system, a method for communicating over a
480 channel having at least one input and at least one output, and having a plurality of either inputs
481 or outputs, said method comprising the steps of:

482 dividing said channel into a plurality of subchannels, each
483 subchannel corresponding to a combination of spatial direction and an input bin of a
484 substantially orthogonalizing procedure; and

485 communicating symbols over one or more of said plurality of
486 subchannels.

487
488 110. In a digital communication system, a method for preparing a sequence of
489 symbols for transmission via a plurality of inputs of a channel, comprising the steps of:

490 a) inputting said symbols of said sequence into a plurality of
491 input corresponding to a plurality of subchannels of said channel, each subchannel
492 corresponding to an input bin of a transmitter substantially orthogonalizing procedure and a
493 channel input; and

494 b) applying, independently for each said channel input, said
495 transmitter substantially orthogonalizing procedure to said symbols assigned to each said
496 channel input.

497
498 111. A method of processing a sequence of symbols received via a plurality of
499 outputs of a channel, said method comprising the steps of:

500 a) applying a substantially orthogonalizing procedure to said
501 sequence of symbols, said procedure being applied independently for each of said plurality of
502 channel outputs, each output symbol of said substantially orthogonalizing procedure
503 corresponding to a subchannel identified by a combination of a particular output bin and a
504 particular one of said channel outputs; and

505 b) processing symbols in said subchannels.

506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
522
523
524
525
526
527
528
529
530
531
532
533
534
535
536

112. In a digital communication system, apparatus for communicating

comprising:

a transmitter that transmits signals from one or more transmitter

antenna elements;

a receiver that receives said signals from via a plurality of

receiver antenna elements;

wherein separation of radiation patterns among either said

transmitter antenna elements or said receiver antenna elements is insufficient to

establish completely isolated spatial directions for communication; and wherein

at least one of said transmitter and said receiver comprises a

processor that processes said signals to increase isolation between spatial directions employed

for communication at a common frequency.

113. The apparatus of claim 112 wherein a channel coupling said plurality of

transmitter antenna elements and receiver antenna elements at said common frequency is

characterized by a spatial channel matrix having a rank greater than one.

114. In a digital communication system, apparatus for communicating

comprising:

a transmitter transmitting signals from one or more transmitter

antenna elements;

a receiver receiving said signals via a plurality of receiver

antenna elements;

wherein separation of radiation patterns among either said

transmitter antenna elements or said receiver antenna elements is insufficient to

establish completely isolated spatial directions for communication; and wherein

at least one of said transmitter and said receiver comprises a

processor that processes said signals to increase isolation between subchannels, each

subchannel associated with a spatial direction and a bin of a substantially orthogonalizing

procedure.

115. The apparatus of claim 114 wherein said substantially orthogonalizing procedure belongs to a group including: an inverse Fast Fourier Transform, a Fast Fourier Transform, a Hilbert transform, a wavelet transform, and processing through a set of bandpass filter/frequency upconverter pairs operating at spaced apart frequencies..

116. In a digital communication system, apparatus for preparing a sequence of symbols for transmission via a plurality of inputs of a channel:

a plurality of parallel subchannel inputs receiving said symbols, said parallel subchannel inputs corresponding to a plurality of subchannels, each subchannel corresponding to an input bin of a transmitter substantially orthogonalizing procedure and a spatial direction; a spatial processor that, for each input bin, spatially processor symbols received by said subchannel inputs corresponding to said input bin, to develop a spatially processed symbol to assign to each combination of channel input and input bin of said transmitter substantially orthogonalizing procedure; and

a substantially orthogonal procedure processor system that applies, independently for each said channel input, said transmitter substantially orthogonalizing procedure to said spatially processed symbols assigned to each said channel input.

117. The apparatus of claim 116 wherein said spatial processor has the effect of making spatial directions of said subchannels into a set of orthogonal spatial dimensions.

118. The apparatus of claim 116 wherein said transmitter substantially orthogonalizing procedure belongs to one of a group consisting of an inverse Fast Fourier Transform, a Fast Fourier Transform, a discrete cosine transform, a Hilbert transform, a wavelet transform, and processing through a plurality of bandpass filter/frequency converter pairs centered at spaced apart frequencies.

119. The apparatus of claim 116 further comprising: a cyclic prefix processor that applies a cyclic prefix processing procedure to a result of said substantially orthogonalizing procedure independently for each channel input.

120. The apparatus of claim 116 wherein said transmitter substantially orthogonalizing procedure is optimized to reduce interference to unintended receivers.

121. The apparatus of claim 116 wherein said spatial processor comprises, for each particular input bin, a weight multiplier that multiplies a vector comprising symbols allocated to subchannels corresponding to said input bin by a beneficial weighting matrix, elements of a result vector of said weight multiplier corresponding to different channel inputs of said plurality of channel inputs.

122. The apparatus of claim 121 wherein said beneficial weighting matrix comprises an input singular matrix of a matrix containing values representing characteristics of said channel, said channel coupling said plurality of channel inputs to one or more channel outputs.

123. The apparatus of claim 121 wherein said beneficial weighting matrix is obtained from a matrix containing values representing characteristics of a channel coupling said plurality of channel inputs to one or more channel outputs.

124. The apparatus of claim 121 wherein said beneficial weighting matrix is chosen to reduce interference to unintended receivers.

125. The apparatus of claim 124 wherein said beneficial weighting matrix is chosen based upon characterization of a desired signal subspace.

126. The apparatus of claim 125 wherein said beneficial weighting matrix is chosen further based upon characterization of an undesired signal subspace.

127. The apparatus of claim 126 wherein characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of time and frequency.

599

600

601

602

603

604

605

606

607

608

609

610

611

612

613

614

615

616

617

618

619

620

621

622

623

624

625

626

627

628

629

128. The apparatus of claim 116 wherein said spatial processor operates so as to reduce interference radiated to unintended receivers.

129. The apparatus of claim 116 wherein said spatial processor, allocates symbols to each combination of channel input and input bin so that there is a one-to-one mapping between spatial direction of a particular subchannel to which a particular symbol has been allocated and channel input to which said particular symbol is allocated.

130. The apparatus of claim 116 further comprising a coder that applies a coding procedure to said symbols prior to processing by said spatial processor.

131. The apparatus of claim 130 wherein said coding procedure is applied independently for each of said subchannels.

132. The apparatus of claim 130 wherein said coding procedure is applied independently for each group of subchannels corresponding to an input bin of said substantially orthogonalizing procedure.

133. The apparatus of claim 130 wherein said coding procedure is applied independently for each group of subchannels corresponding to a particular spatial direction.

134. The apparatus of claim 130 wherein said coding procedure is applied integrally across all of said subchannels.

135. The apparatus of claim 130 wherein said coding procedure belongs to a group consisting of: convolutional coding, Reed-Solomon coding, CRC coding, block coding, trellis coding, turbo coding, and interleaving.

136. The apparatus of claim 130 wherein said coding procedure comprises a trellis coding procedure.

630
631
632
633
634
635
636
637
638
639
640
641
642
643
644
645
646
647
648
649
650
651
652
653
654
655
656
657
658

137. The apparatus of claim 136 wherein a code design of said trellis coding procedure is based on one of: improved bit error performance in interference channels, a periodic product distance metric, exhaustive code polynomial search for favorable bit error rate polynomial searches, combined weighting of product distance and Euclidean distance, product distance of multiple Euclidean distances over short code segments or over a multi-dimensional symbol, and sum of product distances over short code segments.

138. The apparatus of claim 136 wherein a code design of said trellis coding procedure is optimized for performance in a fading matrix channel.

139. The apparatus of claim 130 wherein said coding procedure comprises a one-dimensional trellis coding procedure followed by an interleaving procedure with sequential groups of symbols output by said trellis coding having their internal order maintained by said interleaving procedure.

140. The apparatus of claim 130 wherein said coding procedure comprises a multi-dimensional trellis coding procedure followed by an interleaving procedure with groups of one-dimensional symbols output simultaneously by said multi-dimensional trellis coding procedure having their internal order maintained by said interleaving procedure.

141. The apparatus of claim 130 wherein bit loading and power are allocated to each subchannel.

142. The apparatus of claim 116 further comprising an ARQ system that retransmits symbols via at least one of said spatial processor, and said substantially orthogonalizing procedure processor upon receipt of a notification that said symbols to be retransmitted have been incorrectly received.

143. The apparatus of claim 116 wherein said channel comprises a wireless channel and said plurality of channel inputs are associated with a corresponding plurality of transmitter antenna elements

144. The apparatus of claim 142 wherein said plurality of transmitter antenna elements are co-located.

145. The apparatus of claim 144 wherein said plurality of transmitters are at disparate locations.

146. Apparatus of processing a sequence of symbols received via a plurality of outputs of a channel, said apparatus comprising:

a substantially orthogonalizing procedure processor system that applies a receiver substantially orthogonalizing procedure to said sequence of symbols, said procedure being applied independently for each of said plurality of channel outputs, each output symbol of said substantially orthogonalizing procedure corresponding to a particular output bin and a particular one of said channel outputs; and

a spatial processor that, for each output bin, spatially processes symbols corresponding to said output bin to develop spatially processed symbols assigned to a plurality of spatial directions, each combination of spatial direction and output bin specifying one of a plurality of subchannels.

147. The apparatus of claim 146 wherein said spatial processor operates to make said plurality of spatial directions into a set of orthogonal spatial dimensions.

148. The apparatus of claim 146 wherein said receiver substantially orthogonalizing procedure belongs to one of a group consisting of an inverse Fast Fourier Transform, a Fast Fourier Transform, a discrete cosine transform, a Hilbert transform, a wavelet transform, and processing through a plurality of bandpass filter/frequency converter pairs centered at spaced apart frequencies.

149. The apparatus of claim 146 further comprising: a cyclic prefix processor that applies a cyclic prefix removal procedure to said sequence of symbols independently for each of said channel outputs.

150. The apparatus of claim 146 wherein said receiver substantially orthogonalizing procedure is optimized to reduce deleterious effects of interference from undesired co-channel transmitters.

151. The apparatus of claim 146 wherein said spatial processor comprises, for each particular output bin, a weight multiplier that multiplies a vector comprising symbols of said output bin by a beneficial weighting matrix, elements of a result vector of said multiplier corresponding to different spatial directions.

152. The apparatus of claim 151 wherein said beneficial weighting matrix comprises an output singular vector of a matrix containing values representing characteristics of said channel, said channel coupling one or more channel inputs to said plurality of channel outputs.

153. The apparatus of claim 151 wherein said beneficial weighting matrix is chosen to minimize deleterious effects of interference from undesired transmitters.

154. The apparatus of claim 151 wherein said beneficial weighting matrix is chosen based upon characterization of a desired signal subspace.

155. The apparatus of claim 154 wherein said beneficial weighting matrix is chosen further based upon characterization of an undesired signal subspace.

156. The apparatus of claim 155 wherein said characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of time and frequency.

157. The apparatus of claim 151 wherein said beneficial weighting matrix is obtained from a matrix containing values representing characteristics of said channel, said channel coupling one or more channel inputs and said plurality of channel outputs.

158. The apparatus of claim 157 wherein said beneficial weighting matrix is obtained by an MMSE procedure.

159. The apparatus of claim 146 further comprising: a decoder that applies a decoding procedure to said spatially processed symbols.

160. The apparatus of claim 159 wherein said decoding procedure is applied independently for each of said plurality of subchannels.

161. The apparatus of claim 159 wherein said decoding procedure is applied independently for each group of subchannels corresponding to an output bin of said substantially orthogonalizing procedure.

162. The apparatus of claim 159 wherein said decoding procedure is applied independently for each group of subchannels corresponding to a spatial direction.

163. The apparatus of claim 159 wherein said decoding procedure is applied integrally across all of said plurality of subchannels.

164. The apparatus of claim 159 wherein said decoding procedure belongs to a group consisting of: Reed-Solomon decoding, CRC decoding, block decoding, and de-interleaving.

165. The apparatus of claim 159 wherein said decoding procedure comprises a code sequence detection procedure to decode a trellis code, or convolutional code.

166. The apparatus of claim 165 wherein said code sequence detection procedure employs a metric belonging to a group consisting of: Euclidean metric, weighted Euclidean metric, and Hamming metric.

167. The apparatus of claim 159 wherein said decoding procedure reduces deleterious effects of interference from undesired transmitters.

168. The apparatus of claim 146 further comprising:
a system that sends a retransmission request when received symbols are determined to include errors.

169. The apparatus of claim 170 wherein said channel comprises a wireless channel and said plurality of channel outputs are coupled to a plurality of corresponding receiver antenna elements.

171. The apparatus of claim 170 wherein said plurality of receiver antenna elements are co-located.

172. The apparatus of claim 170 wherein said plurality of receiver antenna elements are at disparate locations.

173. In a digital communication system, apparatus for preparing a sequence of symbols for transmission via a plurality of inputs to a channel, said apparatus comprising:

a substantially orthogonal procedure processor that applies a transmitter substantially orthogonalizing procedure to said sequence of symbols to develop a time domain symbol sequence; and

a weight multiplier that multiplies at least one symbol of said time domain symbol sequence by a weighting vector selected for improved communication to develop a result vector, elements of said result vector corresponding to symbols to be transmitted via individual ones of said plurality of channel inputs.

174. The apparatus of claim 173 wherein said weighting vector comprises an element indicating delay to be applied for a particular one of said plurality of channel inputs.

175. The apparatus of claim 174 wherein said weighting vector is optimized to reduce interference to unintended receivers.

176. The apparatus of claim 173 wherein said weighting vector is chosen based upon characterization of a desired signal subspace.

177. The apparatus of claim 176 wherein said weighting vector is chosen further based upon characterization of an undesired signal subspace.

178. The apparatus of claim 177 wherein said characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of time and frequency.

179. The apparatus of claim 173 wherein said channel comprises a wireless channel and said plurality of channel inputs are associated with a plurality of transmitter antenna elements.

180.

180. In a digital communication system, apparatus for processing a plurality of symbols received via a plurality of outputs of a channel, said apparatus comprising:

a weight multiplier that performs a multiplication of an input vector whose elements correspond to symbols received substantially simultaneously via a selected one of said plurality of channel outputs by a weighting vector to obtain a time domain symbol corresponding to a particular input bin of a receiver substantially orthogonalizing procedure and that repeats said multiplication for successive received symbols to obtain time domain symbols corresponding to successive input bins of said receiver substantially orthogonalizing procedure; and

a substantial orthogonalizing procedure processor that applies said substantially orthogonalizing procedure processor to said obtained time domain symbols.

813
814
815
816
817
818
819
820
821
822
823
824
825
826
827
828
829
830
831
832
833
834
835
836
837
838
839
840
841
842
843

181. The apparatus of claim 180 wherein said weighting vector comprises an element indicating delay to be applied for a particular one of said plurality of channel outputs.

182. The apparatus of claim 180 wherein said weighting vector is optimized to reduce deleterious effects of interference from unintended transmitters.

183. The apparatus of claim 180 wherein said weighting vector is chosen based upon characterization of a desired signal subspace.

184. The apparatus of claim 183 wherein said weighting vector is chosen further based upon characterization of an undesired signal subspace.

185. The apparatus of claim 184 wherein said characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of frequency and time.

186. The apparatus of claim 180 wherein said channel comprises a wireless channel and said plurality of channel outputs are associated with a plurality of corresponding receiver antenna elements.

187. In a digital communication system, apparatus for preparing symbols for transmission via a plurality of inputs of a channel, said apparatus comprising:

a plurality of symbol inputs, each of said symbol inputs receiving a symbol intended for a particular input bin of a transmitter substantially orthogonalizing procedure so that each of a plurality of input bins of said transmitter substantially orthongonalizing procedure has an allocated symbol;

a spatial processor that, for each particular input bin of said plurality of input bins, spatially processes said symbol allocated to said particular input bin to develop a spatially processed symbol vector, each element of said spatially processed symbol vector being assigned to one of said channel inputs; and

844 a substantially orthogonalizing procedure processor that applies said
845 substantially orthogonalizing procedure for a particular channel input, inputs to said
846 substantially orthogonalizing procedure being for each input bin, a symbol of said processed
847 symbol vector for said input bin corresponding to said particular channel input, and that
848 applies said substantially orthogonalizing procedure for each of said plurality of channel inputs.
849

850 188. The apparatus of claim 187 further comprising:
851 a cyclic prefix processor that applies a cyclic prefix processing procedure to
852 outputs of said substantially orthogonalizing procedure independently for each particular
853 channel input.
854

855 189. The apparatus of claim 187 wherein said substantially orthogonalizing
856 procedure is optimized to reduce interference to unintended receivers.
857

858 190. The apparatus of claim 187 wherein said spatial processor comprises:
859 a weight multiplier that multiplies said symbol allocated to said particular input
860 bin by a beneficial weighting vector to obtain said spatially processed symbol vector.
861

862 191. The apparatus of claim 190 wherein said beneficial weighting vector is
863 an input singular vector of a matrix storing values indicative of characteristics of said channel,
864 said channel coupling said plurality of channel inputs and one or more channel outputs.
865

866 192. The apparatus of claim 190 wherein said beneficial weighting vector is
867 chosen to select a beneficial spatial direction for transmission.
868

869 193. The apparatus of claim 191 wherein said beneficial weighting vector is
870 chosen to reduce interference to unintended receivers.
871

872 194. The apparatus of claim 193 wherein said beneficial weighting vector is
873 chosen based upon characterization of a desired signal subspace
874

195. The apparatus of claim 194 wherein said beneficial weighting vector is chosen further based upon characterization of an undesired signal subspace.

196. The apparatus of claim 195 wherein said characterizations of said desired signal subspace and said undesired signal subspace are averaged over at least one of time and frequency.

197. The apparatus of claim 187 wherein said channel comprises a wireless channel and said plurality of channel inputs are associated with a corresponding plurality of transmitter antenna elements.

198. In a digital communication system, apparatus for processing symbols received by a plurality of outputs of a channel comprising:
a substantially orthogonalizing procedure processor that applies a receiver substantially orthogonalizing procedure to symbols received via a particular one of said channel outputs and that said applies said receiver substantially orthogonalizing procedure for each of said channel outputs to develop a result vector for each of a plurality of output bins of said substantially orthogonalizing procedure, said result vector including a result symbol for each of said channel outputs; and

a spatial processor that, for each particular output bin of said substantially orthogonalizing procedure, spatially processes said result vector for said particular output bin to develop a spatially processed result symbol for said particular output bin.

199. The apparatus of claim 198 further comprising: a cyclic prefix removal processor that applies a cyclic prefix removal procedure to symbols independently for each of said channel outputs.

200. The apparatus of claim 198 wherein said substantially orthogonalizing procedure is optimized to reduce deleterious effects of interference from unintended transmitters.

906 201. The apparatus of claim 198 wherein said spatially processor comprises a
907 weight multiplier that multiplies a beneficial weighting vector by said result vector to obtain
908 said spatially processed result symbol.
909

910 202. The apparatus of claim 201 wherein said beneficial weighting vector is
911 an input singular vector of a matrix storing values indicative of characteristics of said channel,
912 said channel coupling one or more channel inputs and said plurality of channel outputs.
913

914 203. The apparatus of claim 201 wherein said beneficial weighting vector is
915 chosen to select a particular spatial direction for reception.
916

917 204. The apparatus of claim 203 wherein said beneficial weighting vector is
918 chosen to minimize deleterious effects of interference from unintended transmitters.
919

920 205. The apparatus of claim 204 wherein said beneficial weighting vector is
921 chosen based upon characterization of a desired signal subspace.
922

923 206. The apparatus of claim 205 wherein said beneficial weighting vector is
924 chosen based upon characterization of an undesired signal subspace.
925

926 207. The apparatus of claim 206 wherein said characterizations of said desired
927 signal subspace and said undesired signal subspace are averaged over at least one of time and
928 frequency.
929

930 208. The apparatus of claim 198 wherein said channel comprises a wireless
931 channel and said plurality of channel outputs are associated with a corresponding plurality of
932 channel outputs.
933

934 209. In a digital communication system including a communication channel
935 having one or more inputs and at least one or more outputs apparatus for determining

characteristics of said channel based on signals received by said one or more outputs,
comprising:

a receiver system receiving via said one or more channel outputs, at least
training symbols transmitted via a particular spatial direction of said channel, being an extent
in symbol periods of a duration of significant terms of an impulse response of a channel;

a substantially orthogonalizing procedure processor that applies a substantially
orthogonalizing procedure processor to said received at least training symbols to obtain a
time domain response for said particular spatial direction; and

an inverse substantially orthogonalizing procedure processor that applies an
inverse of said substantially orthogonalizing procedure to a zero-padded version of said time
domain response to obtain a frequency response for said particular spatial direction.

210. The apparatus of claim 209 wherein said substantially orthogonalizing
procedure comprises an inverse Fast Fourier Transform and said inverse of said substantially
orthogonalizing procedure comprises a Fast Fourier Transform.

211. The apparatus of claim 209 wherein said receiver system receives exactly
training symbols.

212. The apparatus of claim 209 wherein said receiver system, said
substantially orthogonalizing procedure processor and said inverse substantially
orthogonalizing procedure process operate repeatedly for a plurality of spatial directions.

213. The apparatus of claim 209 wherein each of said plurality of spatial
directions corresponds to transmission through one of said plurality of channel inputs
exclusively.

214. The apparatus of claim 209 wherein said training symbols belong to a
burst of N symbols and said characteristics are determined for said burst.

215. The apparatus of claim 214 said receiver system, said substantially orthogonalizing procedure processor and said inverse substantially orthogonalizing procedure process operate repeatedly for a plurality of bursts.

216. The apparatus of claim 215 further comprising:
means for smoothing said time-domain response over successive bursts.

217. The apparatus of claim 216 wherein said smoothing means comprises:
means for Kalman filtering said time-domain response over successive bursts.

218. The apparatus of claim 217 wherein said smoothing means comprises
means for Wiener filtering said time-domain response over successive bursts.

219. The apparatus of claim 209 wherein said communication channel comprises known and unknown components, wherein said effects of said known components are removed by deconvolution, and characteristics of said unknown components are determined by said a), b), c), and d) steps, thereby reducing .

220. In a digital communication system including a communication channel having one or more inputs and one or more outputs, apparatus for determining characteristics of said channel based on signals received via one or more channel outputs, comprising:
a receiver that receives training symbols via said channel outputs; and
a processor that computes characteristics of said channel based on said received training symbols and assumptions that an impulse response of said channel is substantially time-limited and that variation of said impulse response over time is continuous.

221. In a digital communication system, apparatus for communicating over a channel having at least one input and at least one output, and having a plurality of either inputs or outputs, said apparatus comprising:

995 means for dividing said channel into a plurality of subchannels, each subchannel
996 corresponding to a combination of spatial direction and an input bin of a substantially
997 orthogonalizing procedure; and
998 means for communicating symbols over one or more of said plurality of
999 subchannels.

1000

1001 222. In a digital communication system, apparatus for preparing a sequence of
1002 symbols for transmission via a plurality of inputs of a channel, said apparatus comprising:
1003 a plurality of parallel subchannel inputs that receive said sequence of symbols,
1004 said subchannel inputs corresponding to a plurality of subchannels, each subchannel
1005 corresponding to an input bin of a transmitter substantially orthogonalizing procedure and a
1006 channel input; and
1007 a substantially orthogonalizing procedure processor that applies, independently
1008 for each said channel input, said transmitter substantially orthogonalizing procedure to said
1009 symbols assigned to each said channel input.

1010

1011 223. Apparatus for processing a sequence of symbols received via a plurality
1012 of outputs of a channel, said apparatus comprising the steps of:
1013 a substantially orthogonalizing procedure processor that applies a receiver
1014 substantially orthogonalizing procedure to said sequence of symbols, said procedure being
1015 applied independently for each of said plurality of channel outputs, each output symbol of said
1016 receiver substantially orthogonalizing procedure corresponding to a subchannel identified by a
1017 combination of a particular output bin and a particular one of said channel outputs; and
1018 a processor that processes symbols in said subchannels.

ABSTRACT OF THE DISCLOSURE

A space-time signal processing system with advantageously reduced complexity. The system may take advantage of multiple transmitter antenna elements and/or multiple receiver antenna elements, or multiple polarizations of a single transmitter antenna element and/or single receiver antenna element. The system is not restricted to wireless contexts and may exploit any channel having multiple inputs or multiple outputs and certain other characteristics. Multi-path effects in a transmission medium cause a multiplicative increase in capacity.

Figure 1 shows a block diagram of a transmitter system. The system consists of four main blocks connected in series: 1. Encoder & Interleaving (10), 2. Training Symbol Injection (20), 3. Tx Space-Freq. Pre-processor (30), and 4. Modulation & RF System (40). The output of the Modulation & RF System is connected to a Tx Antenna Array (50). The input to the Encoder & Interleaving block is labeled 'Input Data' and '2'.

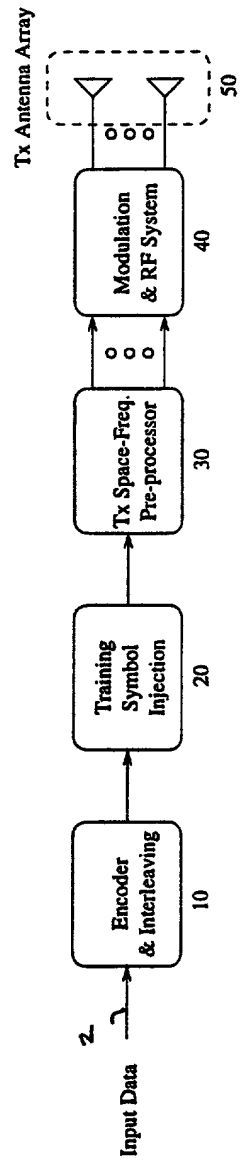
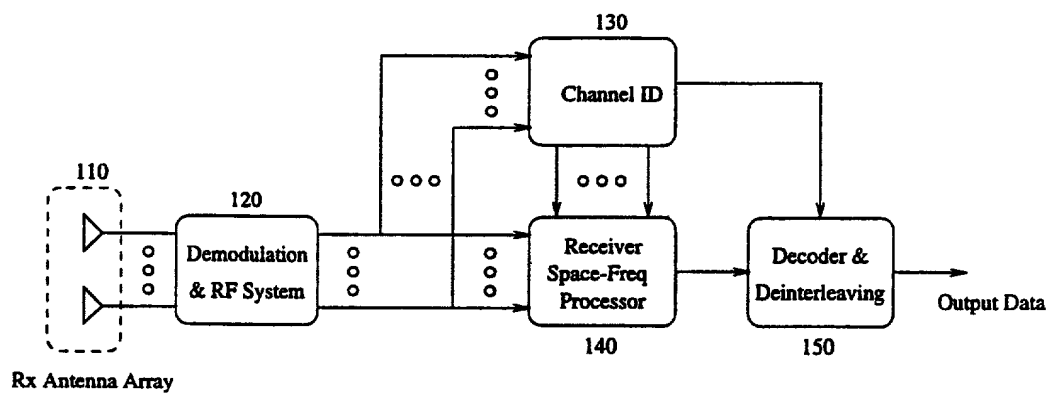


Figure 1



Multipath can be more than one reflected or refracted path in a wireless propagation channel with antenna elements that have one polarization.

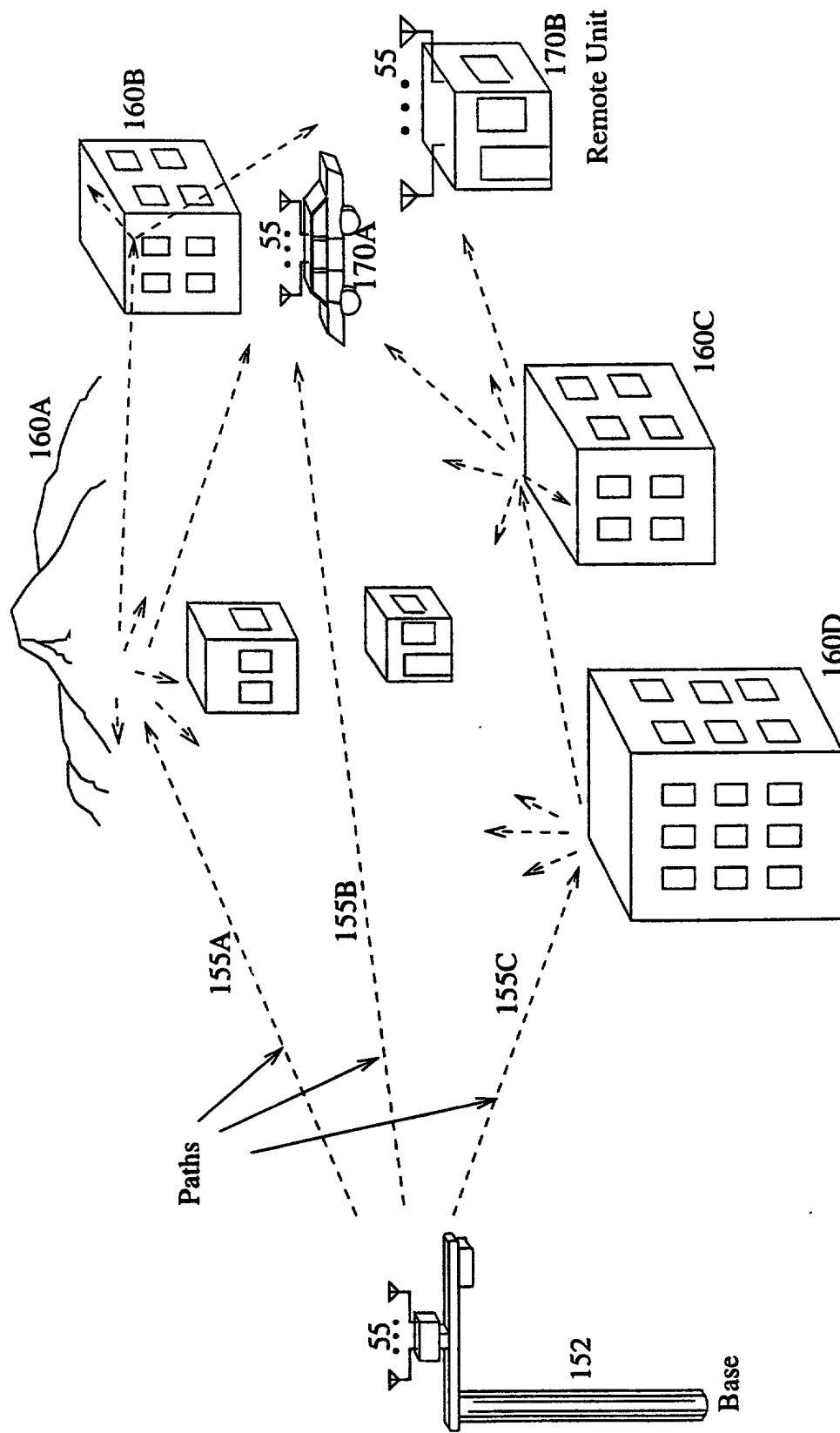


Figure 4

Multipath can be one or more paths with polarization A and one or more paths with polarization B. The two sets of paths may or may not be orthogonal.

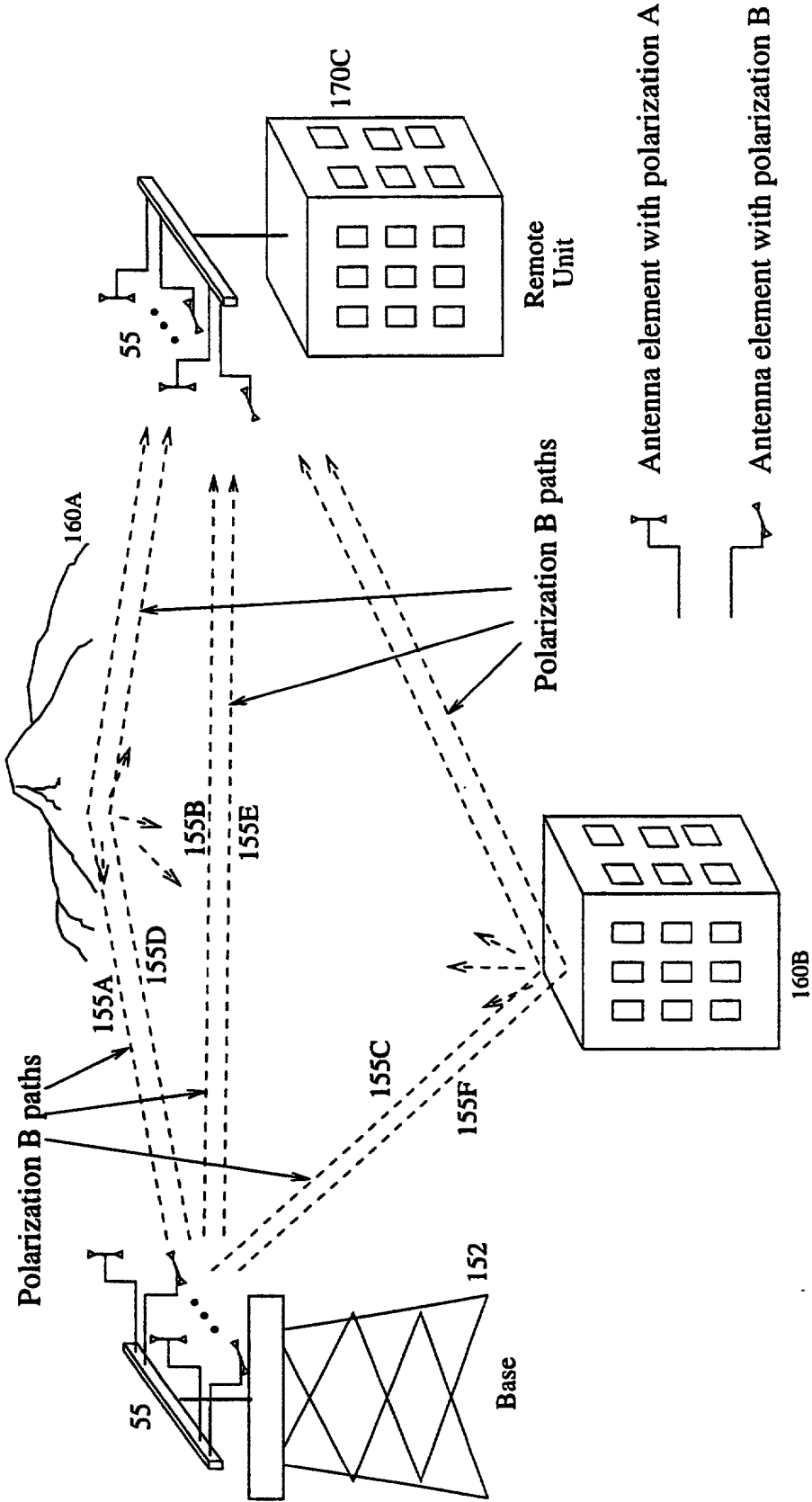


Figure 5

152A Base
 152B Base
 153A
 153B
 153C
 153D
 160A
 160B
 160C
 160D
 160E
 160F
 160G
 170A
 170B
 170C
 170D
 170E
 170F
 170G
 170H
 170I
 170J
 170K
 170L
 170M
 170N
 170O
 170P
 170Q
 170R
 170S
 170T
 170U
 170V
 170W
 170X
 170Y
 170Z
 171A
 171B
 171C
 171D
 171E
 171F
 171G
 171H
 171I
 171J
 171K
 171L
 171M
 171N
 171O
 171P
 171Q
 171R
 171S
 171T
 171U
 171V
 171W
 171X
 171Y
 171Z
 172A
 172B
 172C
 172D
 172E
 172F
 172G
 172H
 172I
 172J
 172K
 172L
 172M
 172N
 172O
 172P
 172Q
 172R
 172S
 172T
 172U
 172V
 172W
 172X
 172Y
 172Z
 173A
 173B
 173C
 173D
 173E
 173F
 173G
 173H
 173I
 173J
 173K
 173L
 173M
 173N
 173O
 173P
 173Q
 173R
 173S
 173T
 173U
 173V
 173W
 173X
 173Y
 173Z
 174A
 174B
 174C
 174D
 174E
 174F
 174G
 174H
 174I
 174J
 174K
 174L
 174M
 174N
 174O
 174P
 174Q
 174R
 174S
 174T
 174U
 174V
 174W
 174X
 174Y
 174Z
 175A
 175B
 175C
 175D
 175E
 175F
 175G
 175H
 175I
 175J
 175K
 175L
 175M
 175N
 175O
 175P
 175Q
 175R
 175S
 175T
 175U
 175V
 175W
 175X
 175Y
 175Z
 176A
 176B
 176C
 176D
 176E
 176F
 176G
 176H
 176I
 176J
 176K
 176L
 176M
 176N
 176O
 176P
 176Q
 176R
 176S
 176T
 176U
 176V
 176W
 176X
 176Y
 176Z
 177A
 177B
 177C
 177D
 177E
 177F
 177G
 177H
 177I
 177J
 177K
 177L
 177M
 177N
 177O
 177P
 177Q
 177R
 177S
 177T
 177U
 177V
 177W
 177X
 177Y
 177Z
 178A
 178B
 178C
 178D
 178E
 178F
 178G
 178H
 178I
 178J
 178K
 178L
 178M
 178N
 178O
 178P
 178Q
 178R
 178S
 178T
 178U
 178V
 178W
 178X
 178Y
 178Z
 179A
 179B
 179C
 179D
 179E
 179F
 179G
 179H
 179I
 179J
 179K
 179L
 179M
 179N
 179O
 179P
 179Q
 179R
 179S
 179T
 179U
 179V
 179W
 179X
 179Y
 179Z
 180A
 180B
 180C
 180D
 180E
 180F
 180G
 180H
 180I
 180J
 180K
 180L
 180M
 180N
 180O
 180P
 180Q
 180R
 180S
 180T
 180U
 180V
 180W
 180X
 180Y
 180Z
 181A
 181B
 181C
 181D
 181E
 181F
 181G
 181H
 181I
 181J
 181K
 181L
 181M
 181N
 181O
 181P
 181Q
 181R
 181S
 181T
 181U
 181V
 181W
 181X
 181Y
 181Z
 182A
 182B
 182C
 182D
 182E
 182F
 182G
 182H
 182I
 182J
 182K
 182L
 182M
 182N
 182O
 182P
 182Q
 182R
 182S
 182T
 182U
 182V
 182W
 182X
 182Y
 182Z
 183A
 183B
 183C
 183D
 183E
 183F
 183G
 183H
 183I
 183J
 183K
 183L
 183M
 183N
 183O
 183P
 183Q
 183R
 183S
 183T
 183U
 183V
 183W
 183X
 183Y
 183Z
 184A
 184B
 184C
 184D
 184E
 184F
 184G
 184H
 184I
 184J
 184K
 184L
 184M
 184N
 184O
 184P
 184Q
 184R
 184S
 184T
 184U
 184V
 184W
 184X
 184Y
 184Z
 185A
 185B
 185C
 185D
 185E
 185F
 185G
 185H
 185I
 185J
 185K
 185L
 185M
 185N
 185O
 185P
 185Q
 185R
 185S
 185T
 185U
 185V
 185W
 185X
 185Y
 185Z
 186A
 186B
 186C
 186D
 186E
 186F
 186G
 186H
 186I
 186J
 186K
 186L
 186M
 186N
 186O
 186P
 186Q
 186R
 186S
 186T
 186U
 186V
 186W
 186X
 186Y
 186Z
 187A
 187B
 187C
 187D
 187E
 187F
 187G
 187H
 187I
 187J
 187K
 187L
 187M
 187N
 187O
 187P
 187Q
 187R
 187S
 187T
 187U
 187V
 187W
 187X
 187Y
 187Z
 188A
 188B
 188C
 188D
 188E
 188F
 188G
 188H
 188I
 188J
 188K
 188L
 188M
 188N
 188O
 188P
 188Q
 188R
 188S
 188T
 188U
 188V
 188W
 188X
 188Y
 188Z
 189A
 189B
 189C
 189D
 189E
 189F
 189G
 189H
 189I
 189J
 189K
 189L
 189M
 189N
 189O
 189P
 189Q
 189R
 189S
 189T
 189U
 189V
 189W
 189X
 189Y
 189Z
 190A
 190B
 190C
 190D
 190E
 190F
 190G
 190H
 190I
 190J
 190K
 190L
 190M
 190N
 190O
 190P
 190Q
 190R
 190S
 190T
 190U
 190V
 190W
 190X
 190Y
 190Z
 191A
 191B
 191C
 191D
 191E
 191F
 191G
 191H
 191I
 191J
 191K
 191L
 191M
 191N
 191O
 191P
 191Q
 191R
 191S
 191T
 191U
 191V
 191W
 191X
 191Y
 191Z
 192A
 192B
 192C
 192D
 192E
 192F
 192G
 192H
 192I
 192J
 192K
 192L
 192M
 192N
 192O
 192P
 192Q
 192R
 192S
 192T
 192U
 192V
 192W
 192X
 192Y
 192Z
 193A
 193B
 193C
 193D
 193E
 193F
 193G
 193H
 193I
 193J
 193K
 193L
 193M
 193N
 193O
 193P
 193Q
 193R
 193S
 193T
 193U
 193V
 193W
 193X
 193Y
 193Z
 194A
 194B
 194C
 194D
 194E
 194F
 194G
 194H
 194I
 194J
 194K
 194L
 194M
 194N
 194O
 194P
 194Q
 194R
 194S
 194T
 194U
 194V
 194W
 194X
 194Y
 194Z
 195A
 195B
 195C
 195D
 195E
 195F
 195G
 195H
 195I
 195J
 195K
 195L
 195M
 195N
 195O
 195P
 195Q
 195R
 195S
 195T
 195U
 195V
 195W
 195X
 195Y
 195Z
 196A
 196B
 196C
 196D
 196E
 196F
 196G
 196H
 196I
 196J
 196K
 196L
 196M
 196N
 196O
 196P
 196Q
 196R
 196S
 196T
 196U
 196V
 196W
 196X
 196Y
 196Z
 197A
 197B
 197C
 197D
 197E
 197F
 197G
 197H
 197I
 197J
 197K
 197L
 197M
 197N
 197O
 197P
 197Q
 197R
 197S
 197T
 197U
 197V
 197W
 197X
 197Y
 197Z
 198A
 198B
 198C
 198D
 198E
 198F
 198G
 198H
 198I
 198J
 198K
 198L
 198M
 198N
 198O
 198P
 198Q
 198R
 198S
 198T
 198U
 198V
 198W
 198X
 198Y
 198Z
 199A
 199B
 199C
 199D
 199E
 199F
 199G
 199H
 199I
 199J
 199K
 199L
 199M
 199N
 199O
 199P
 199Q
 199R
 199S
 199T
 199U
 199V
 199W
 199X
 199Y
 199Z
 200A
 200B
 200C
 200D
 200E
 200F
 200G
 200H
 200I
 200J
 200K
 200L
 200M
 200N
 200O
 200P
 200Q
 200R
 200S
 200T
 200U
 200V
 200W
 200X
 200Y
 200Z
 201A
 201B
 201C
 201D
 201E
 201F
 201G
 201H
 201I
 201J
 201K
 201L
 201M
 201N
 201O
 201P
 201Q
 201R
 201S
 201T
 201U
 201V
 201W
 201X
 201Y
 201Z
 202A
 202B
 202C
 202D
 202E
 202F
 202G
 202H
 202I
 202J
 202K
 202L
 202M
 202N
 202O
 202P
 202Q
 202R
 202S
 202T
 202U
 202V
 202W
 202X
 202Y
 202Z
 203A
 203B
 203C
 203D
 203E
 203F
 203G
 203H
 203I
 203J
 203K
 203L
 203M
 203N
 203O
 203P
 203Q
 203R
 203S
 203T
 203U
 203V
 203W
 203X
 203Y
 203Z
 204A
 204B
 204C
 204D
 204E
 204F
 204G
 204H
 204I
 204J
 204K
 204L
 204M
 204N
 204O
 204P
 204Q
 204R
 204S
 204T
 204U
 204V
 204W
 204X
 204Y
 204Z
 205A
 205B
 205C
 205D
 205E
 205F
 205G
 205H
 205I
 205J
 205K
 205L
 205M
 205N
 205O
 205P
 205Q
 205R
 205S
 205T
 205U
 205V
 205W
 205X
 205Y
 205Z
 206A
 206B
 206C
 206D
 206E
 206F
 206G
 206H
 206I
 206J
 206K
 206L
 206M
 206N
 206O
 206P
 206Q
 206R
 206S
 206T
 206U
 206V
 206W
 206X
 206Y
 206Z
 207A
 207B
 207C
 207D
 207E
 207F
 207G
 207H
 207I
 207J
 207K
 207L
 207M
 207N
 207O
 207P
 207Q
 207R
 207S
 207T
 207U
 207V
 207W
 207X
 207Y
 207Z
 208A
 208B
 208C
 208D
 208E
 208F
 208G
 208H
 208I
 208J
 208K
 208L
 208M
 208N
 208O
 208P
 208Q
 208R
 208S
 208T
 208U
 208V
 208W
 208X
 208Y
 208Z
 209A
 209B
 209C
 209D
 209E
 209F
 209G
 209H
 209I
 209J
 209K
 209L
 209M
 209N
 209O
 209P
 209Q
 209R
 209S
 209T
 209U
 209V
 209W
 209X
 209Y
 209Z
 210A
 210B
 210C
 210D
 210E
 210F
 210G
 210H
 210I
 210J
 210K
 210L
 210M
 210N
 210O
 210P
 210Q
 210R
 210S
 210T
 210U
 210V
 210W
 210X
 210Y
 210Z
 211A
 211B
 211C
 211D
 211E
 211F
 211G
 211H
 211I
 211J
 211K
 211L
 211M
 211N
 211O
 211P
 211Q
 211R
 211S
 211T
 211U
 211V
 211W
 211X
 211Y
 211Z
 212A
 212B
 212C
 212D
 212E
 212F
 212G
 212H
 212I
 212J
 212K
 212L
 212M
 212N
 212O
 212P
 212Q
 212R
 212S
 212T
 212U
 212V
 212W
 212X
 212Y
 212Z
 213A
 213B
 213C
 213D
 213E
 213F
 213G
 213H
 213I
 213J
 213K
 213L
 213M
 213N
 213O
 213P
 213Q
 213R
 213S
 213T
 213U
 213V
 213W
 213X
 213Y
 213Z
 214A
 214B
 214C
 214D
 214E
 214F
 214G
 214H
 214I
 214J
 214K
 214L
 214M
 214N
 214O
 214P
 214Q
 214R
 214S
 214T
 214U
 214V
 214W
 214X
 214Y
 214Z
 215A
 215B
 215C
 215D
 215E
 215F
 215G
 215H
 215I
 215J
 215K
 215L
 215M
 215N
 215O
 215P
 215Q
 215R
 215S
 215T
 215U
 215V
 215W
 215X
 215Y
 215Z
 216A
 216B
 216C
 216D
 216E
 216F
 216G
 216H
 216I
 216J
 216K
 216L
 216M
 216N
 216O
 216P
 216Q
 216R
 216S
 216T
 216U
 216V
 216W
 216X
 216Y
 216Z
 217A
 217B
 217C
 217D
 217E
 217F
 217G
 217H
 217I
 217J
 217K
 217L
 217M
 217N
 217O
 217P
 217Q
 217R
 217S
 217T
 217U
 217V
 217W
 217X
 217Y
 217Z
 218A
 218B
 218C
 218D
 218E
 218F
 218G
 218H
 218I
 218J
 218K
 218L
 218M
 218N
 218O
 218P
 218Q
 218R
 218S
 218T
 218U
 218V
 218W
 218X
 218Y
 218Z
 219A
 219B
 219C
 219D
 219E
 219F
 219G
 219H
 219I
 219J
 219K
 219L
 219M
 219N
 219O
 219P
 219Q
 219R
 219S
 219T
 219U
 219V
 219W
 219X
 219Y
 219Z
 220A
 220B
 220C
 220D
 220E
 220F
 220G
 220H
 220I
 220J
 220K
 220L
 220M
 220N
 220O
 220P
 220Q
 220R
 220S
 220T
 220U
 220V
 220W
 220X
 220Y
 220Z
 221A
 221B
 221C
 221D
 221E
 221F
 221G
 221H
 221I
 221J
 221K
 221L
 221M
 221N
 221O
 221P
 221Q
 221R
 221S
 221T
 221U
 221V
 221W
 221X
 221Y
 221Z
 222A
 222B
 222C
 222D
 222E
 222F
 222G
 222H

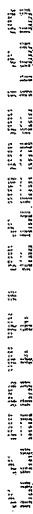


Figure 7

| Variable | Mean | SD | Min | Max |
|-----------------------|--------------|----------|----------|----------|
| Age | 38.5 | 10.2 | 25 | 55 |
| Gender | Male | | | |
| Marital Status | Married | | | |
| Education | High School | | | |
| Occupation | Manager | | | |
| Income | \$45,000 | \$15,000 | \$20,000 | \$70,000 |
| Health Status | Good | | | |
| Exercise Frequency | 3 times/week | | | |
| Dietary Habits | Healthy | | | |
| Stress Level | Low | | | |
| Sleep Quality | Good | | | |
| Work-Life Balance | Good | | | |
| Family Support | High | | | |
| Community Involvement | Active | | | |
| Life Satisfaction | High | | | |
| Overall Well-being | High | | | |

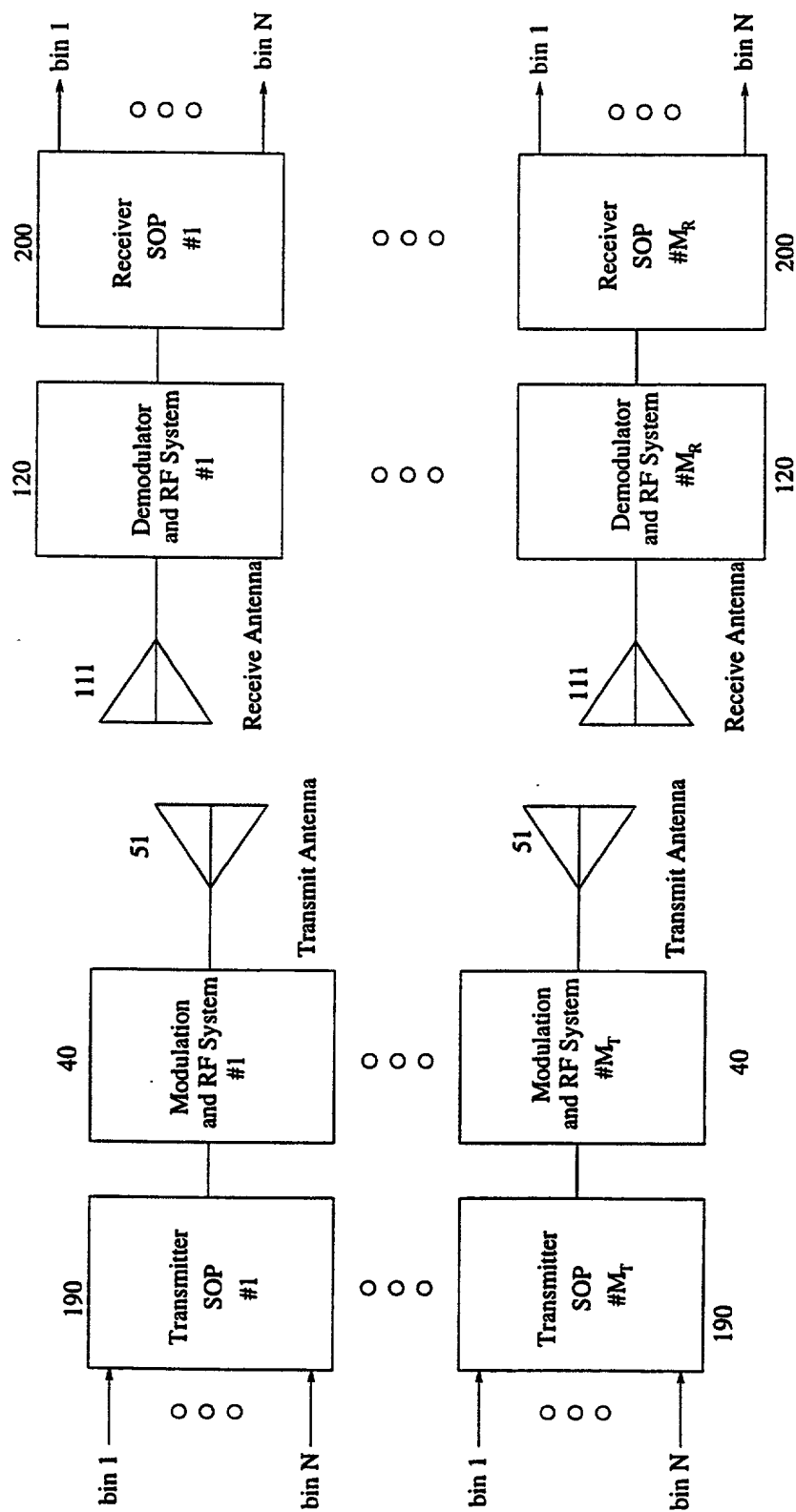


Figure 9

210A TSW (1,1) 210B TSW (1,2) 210C TSW (1,M) 210D TSW (1,N)

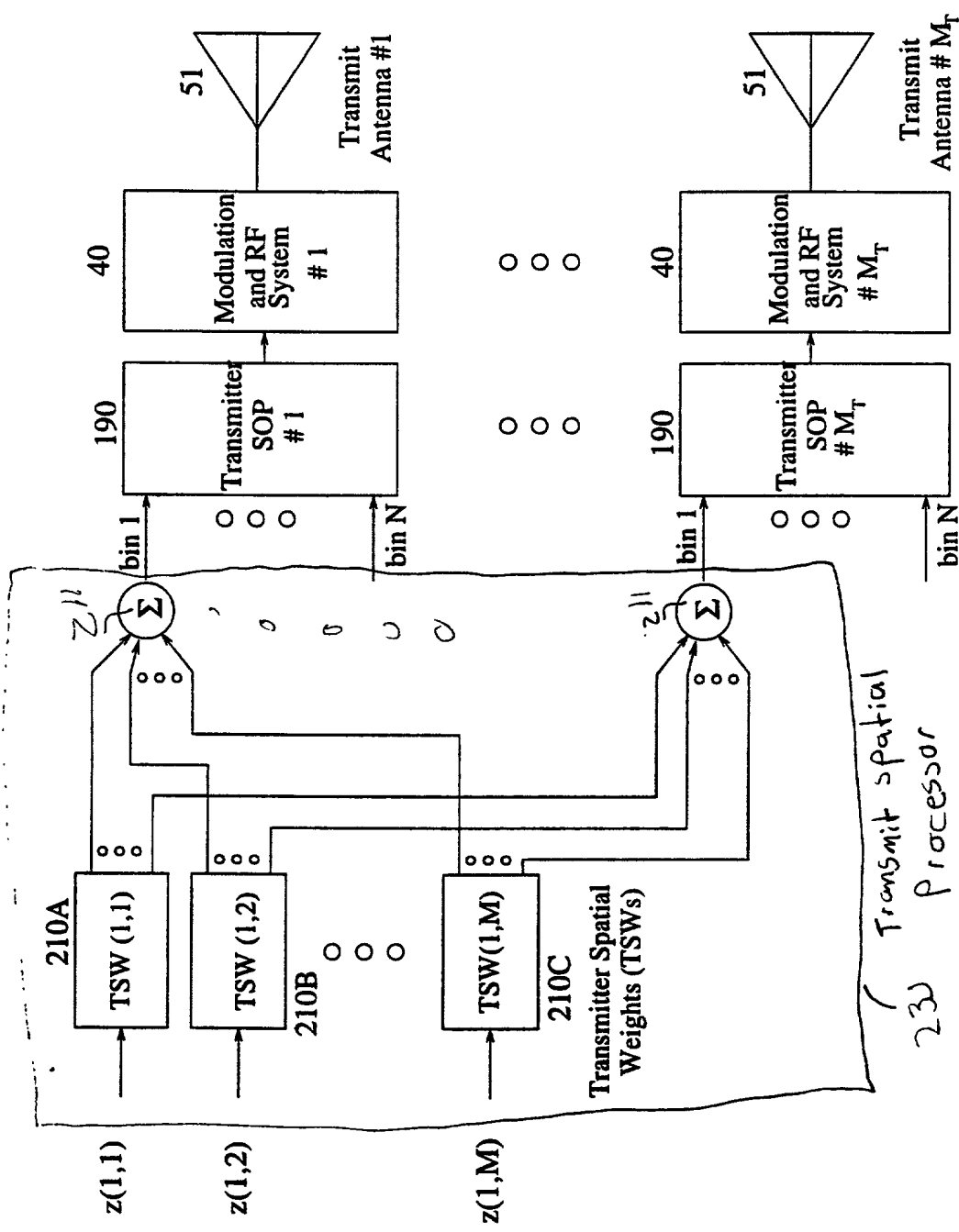


Figure 11

FIG. 12 is a block diagram of a receiver system 100. The receiver system 100 includes a plurality of receive antennas 110, a plurality of demodulation and RF systems 120, a plurality of receiver SOPs 200, and a receiver spatial processor 240. The receiver system 100 is configured to receive signals from the receive antennas 110 and process the signals to produce output signals x(1,1), x(1,2), ..., x(1,M).

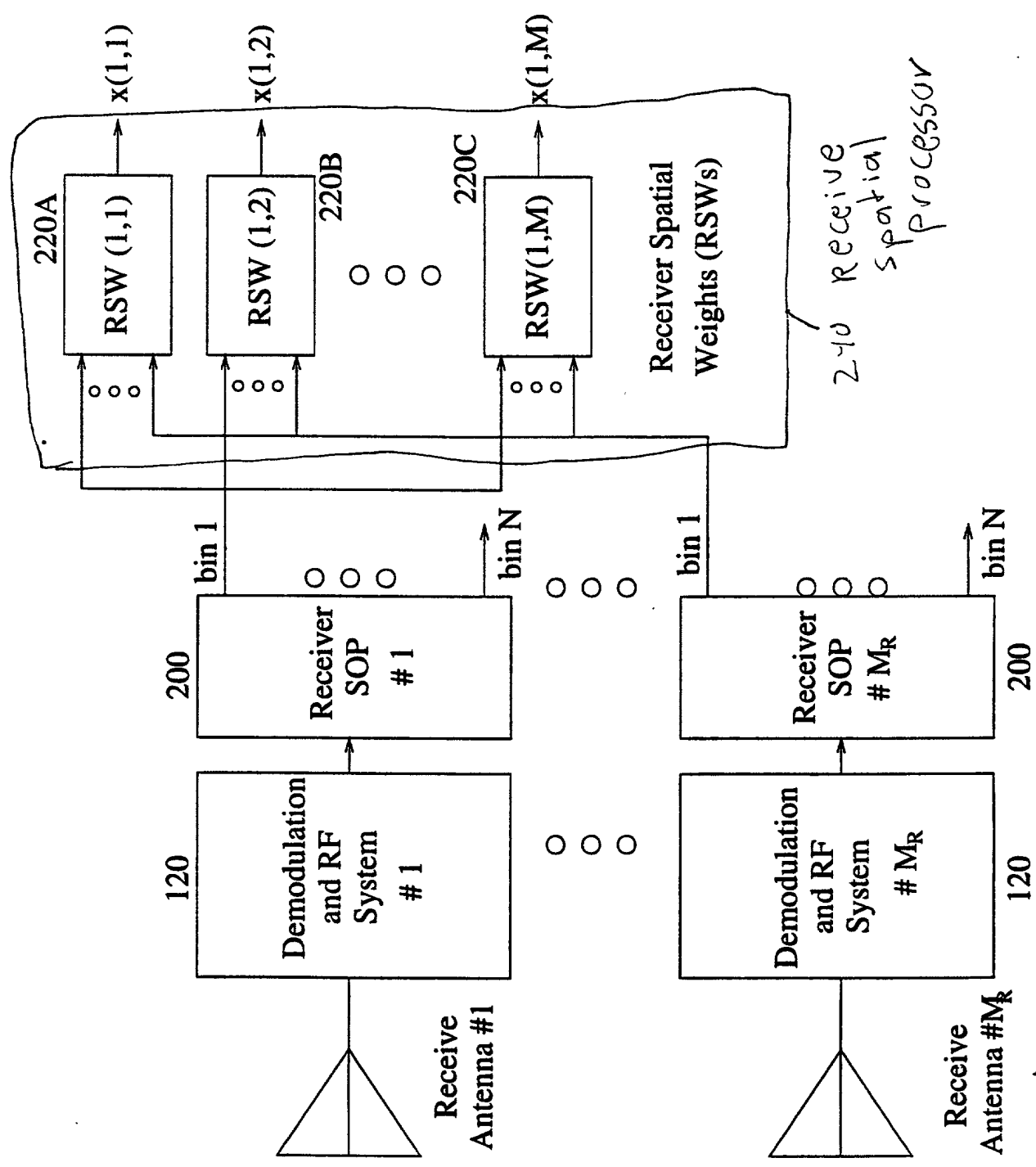


Figure 12

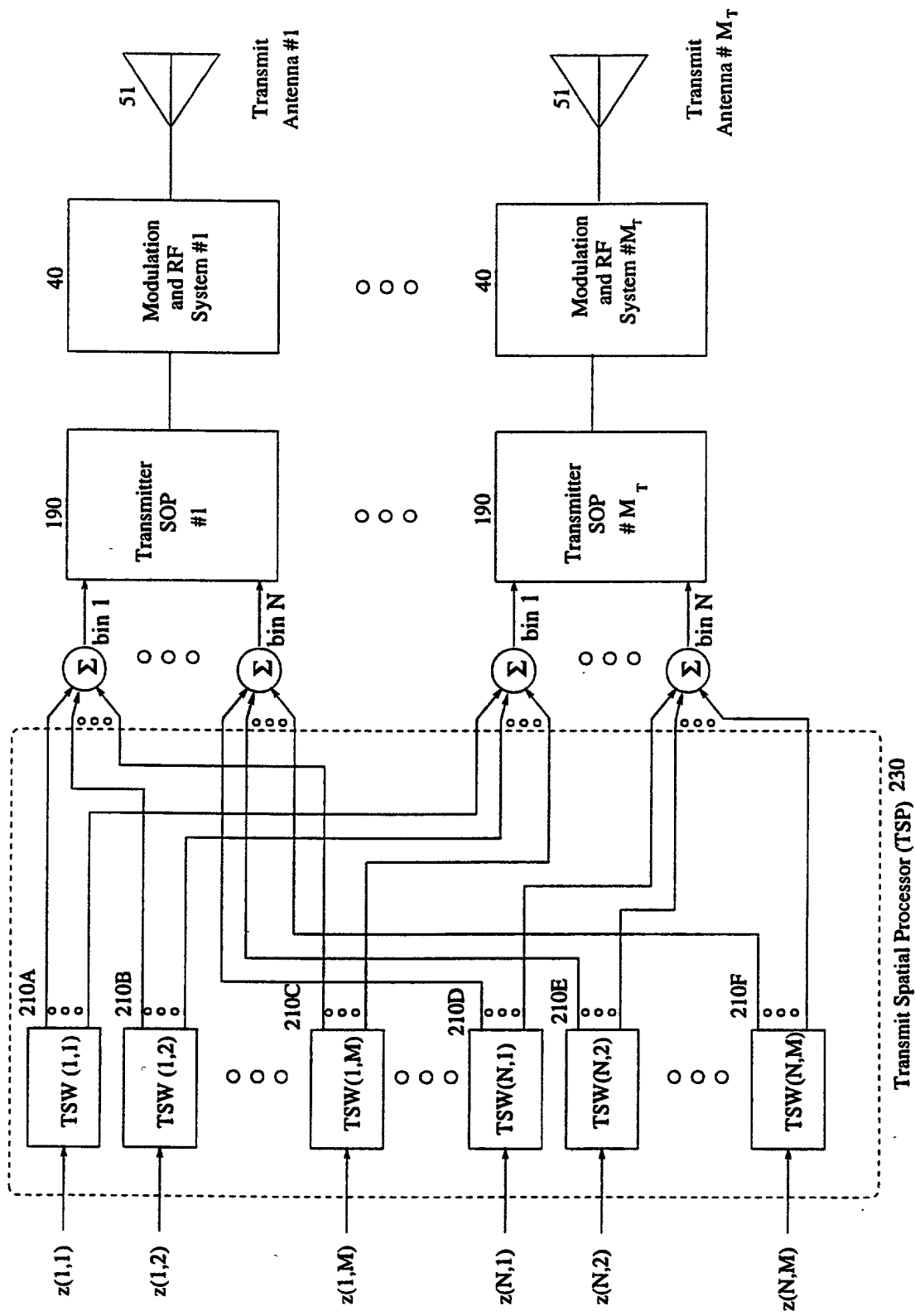


Figure 13

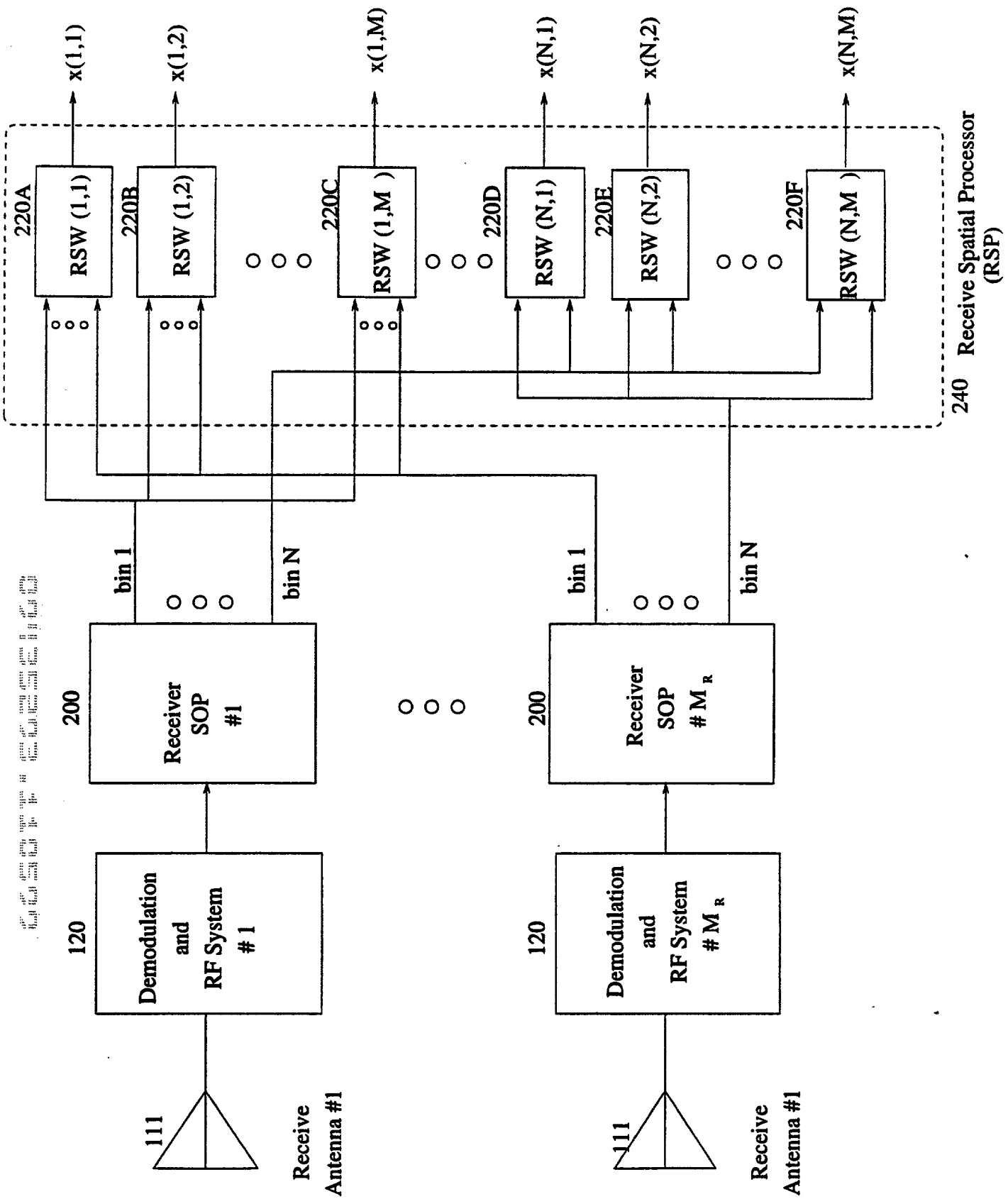


Figure 14

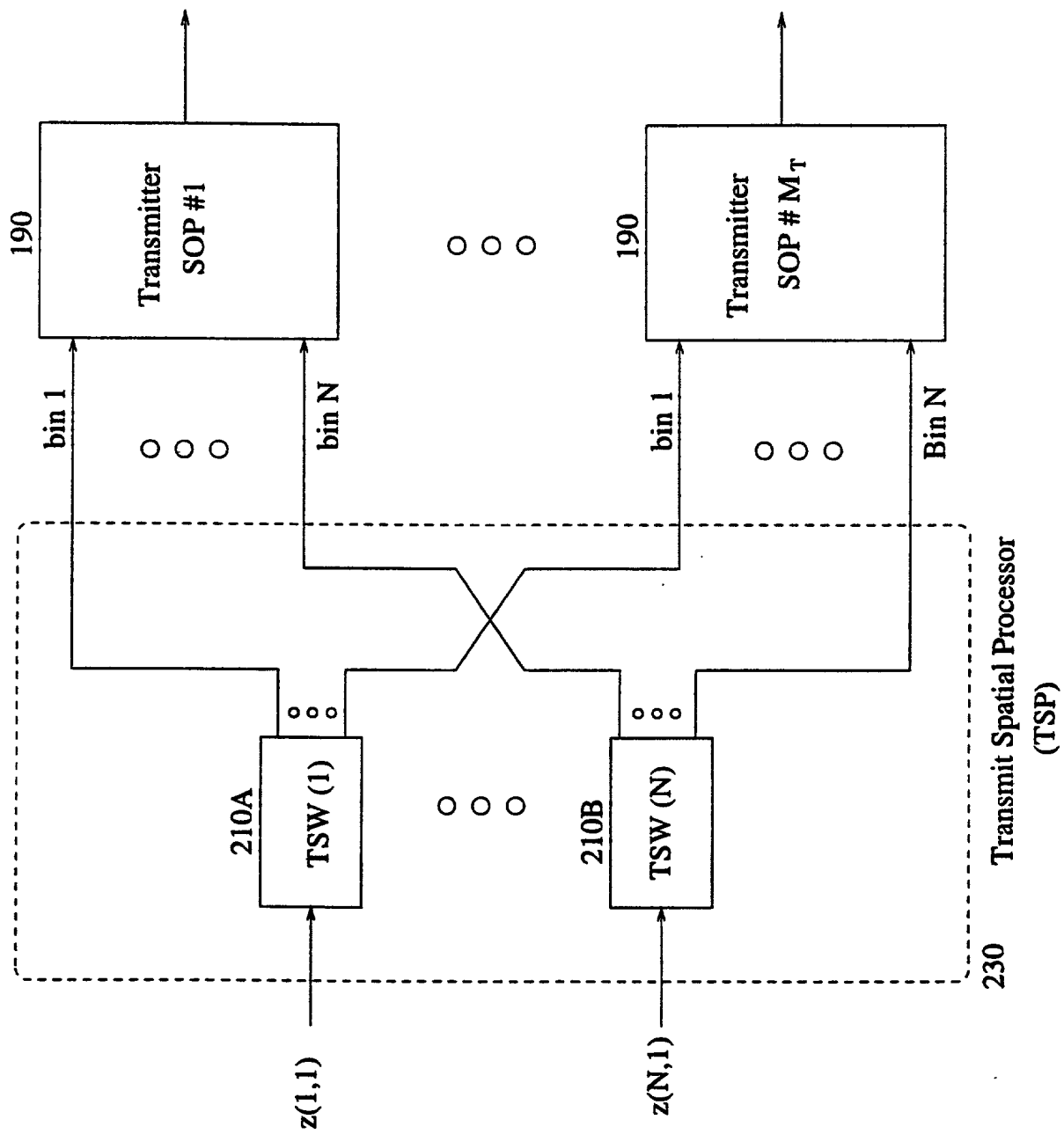


Figure 15

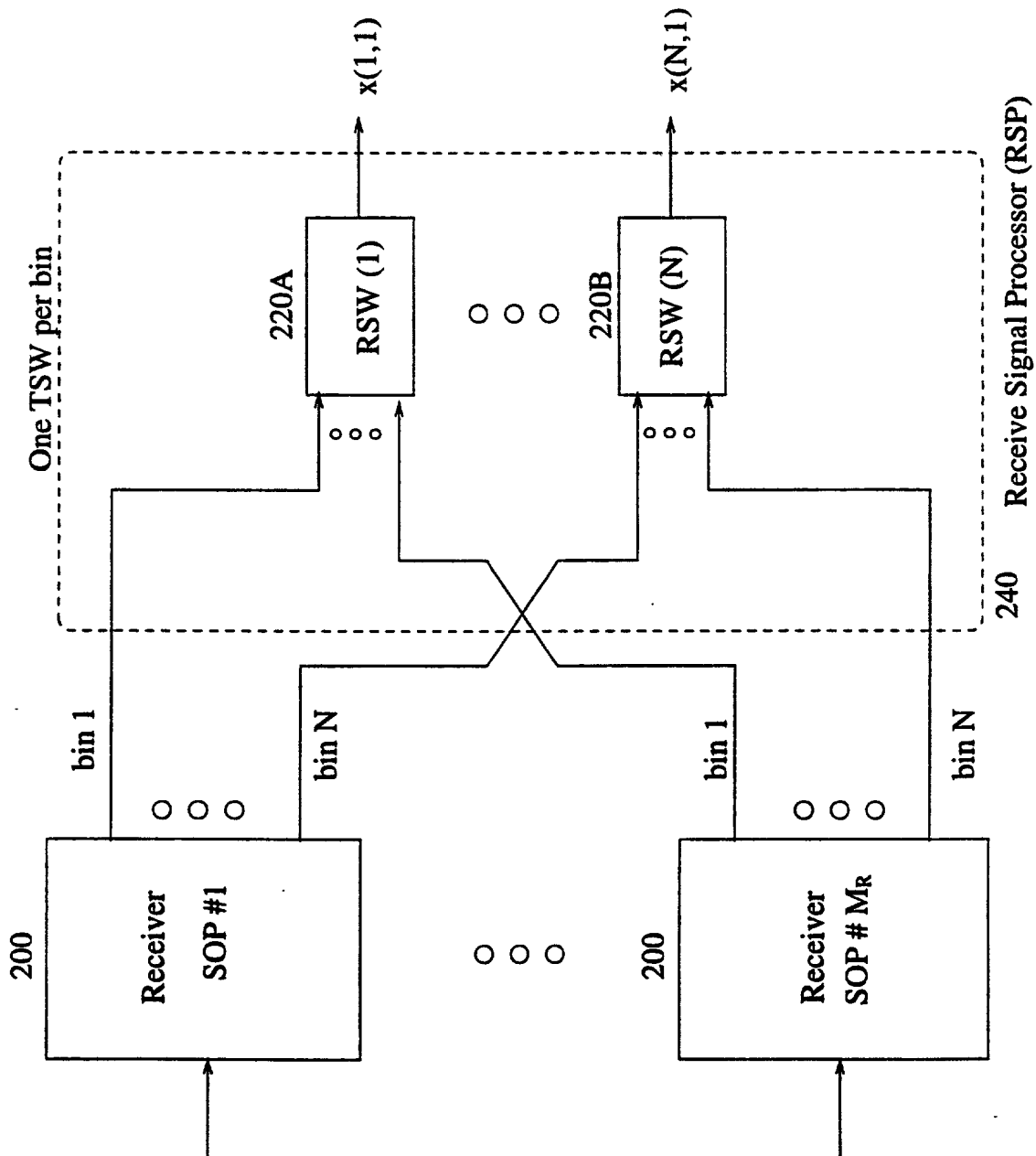


Figure 16

190 210A 210B 40 51
 Transmitter SOP #1 TSW #1 Modulation and RF System #1 Transmit Antenna #1
 Transmitter SOP #M TSW #M Modulation and RF System #M_T Transmit Antenna #M_T

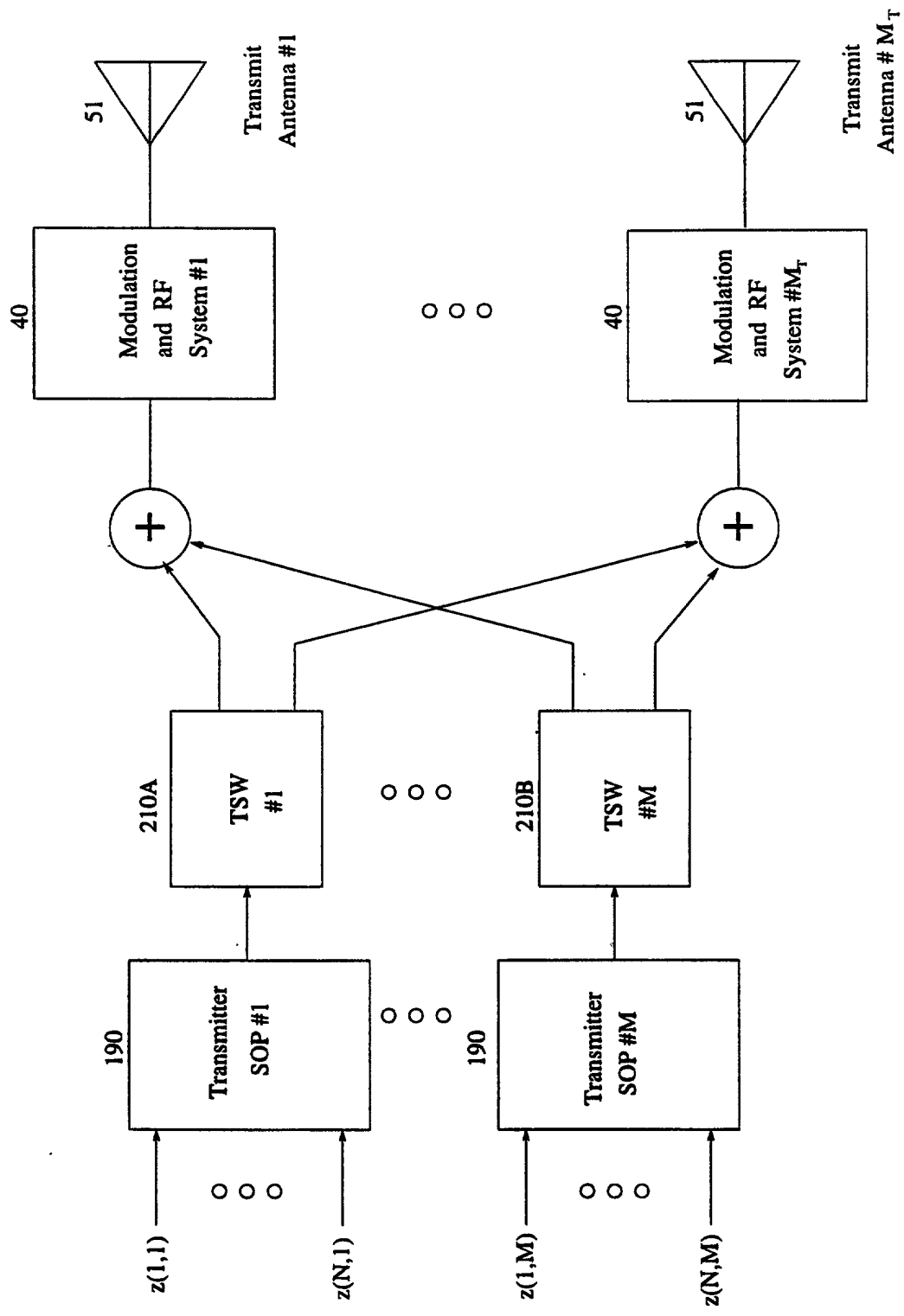


Figure 17

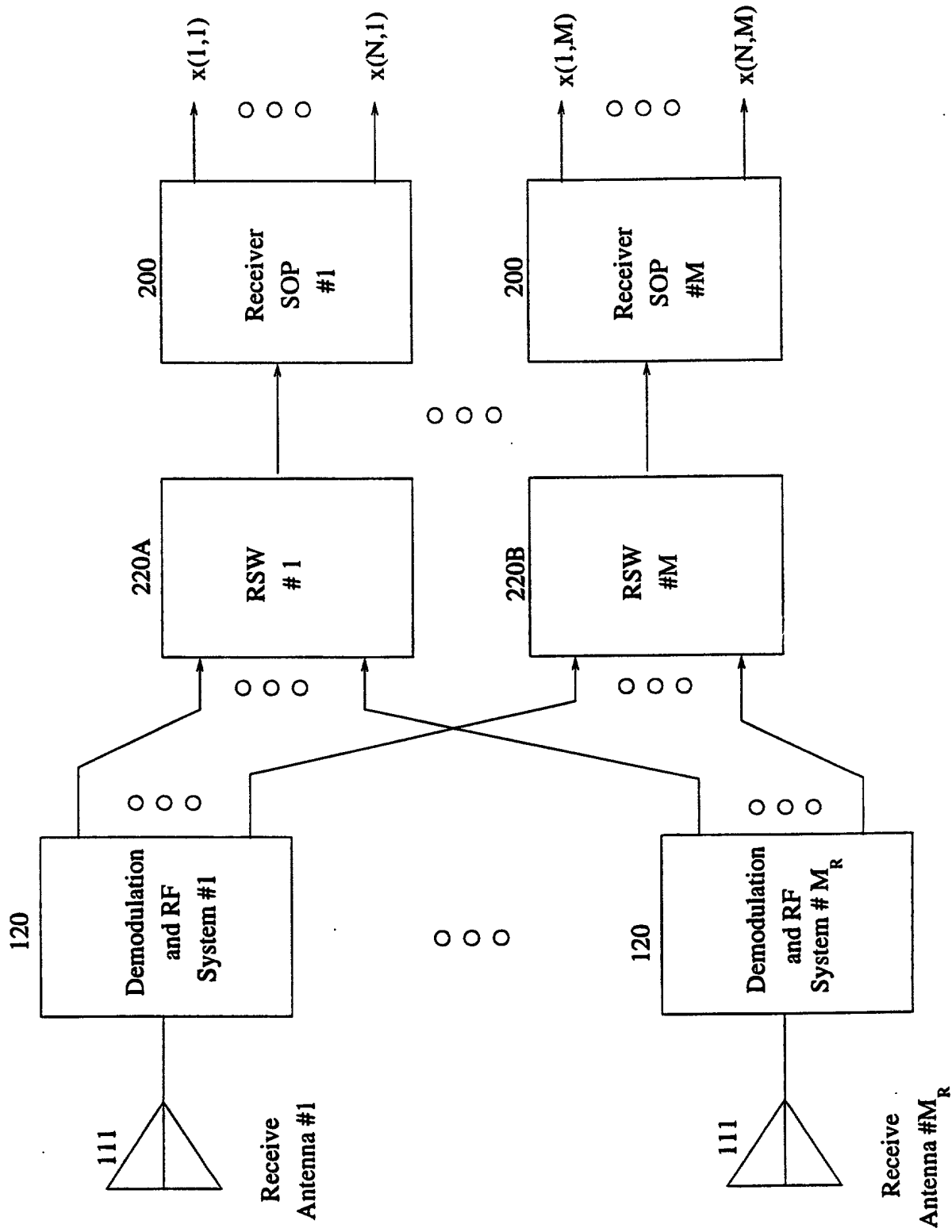


Figure 18

FIG. 20 is a block diagram of a transmitter system. The system includes a Data input, a series of Encoder & Interleaving blocks (1, 2, ..., M), and a series of Transmitter Spatial Weights (TSWs) (1,1, 1,2, ..., 1,M, ..., N,1, N,2, ..., N,M). The Data input is connected to the Encoder & Interleaving blocks. The output of the Encoder & Interleaving blocks is connected to the TSW blocks. The TSW blocks are connected to the output of the system.

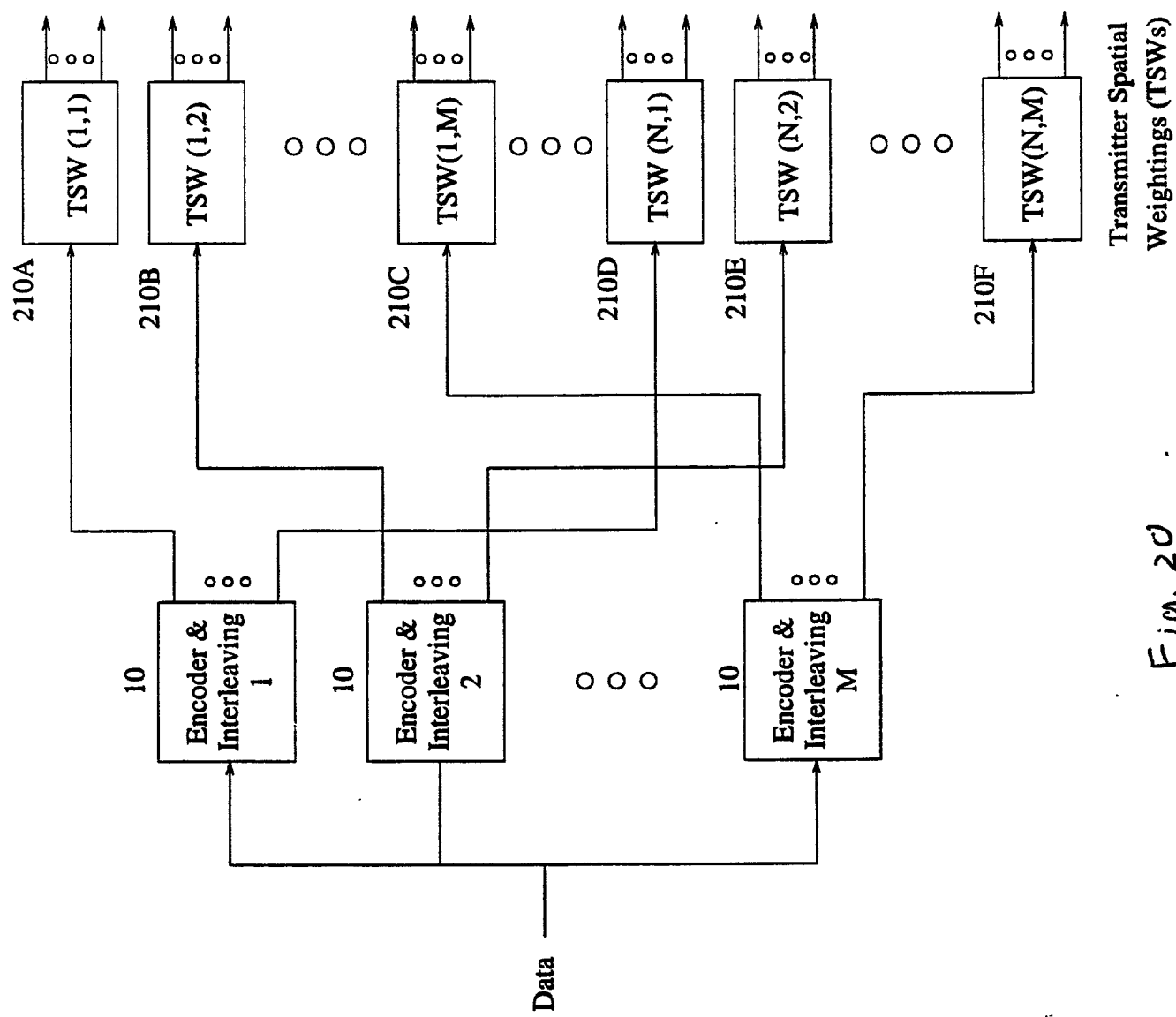


Fig. 20

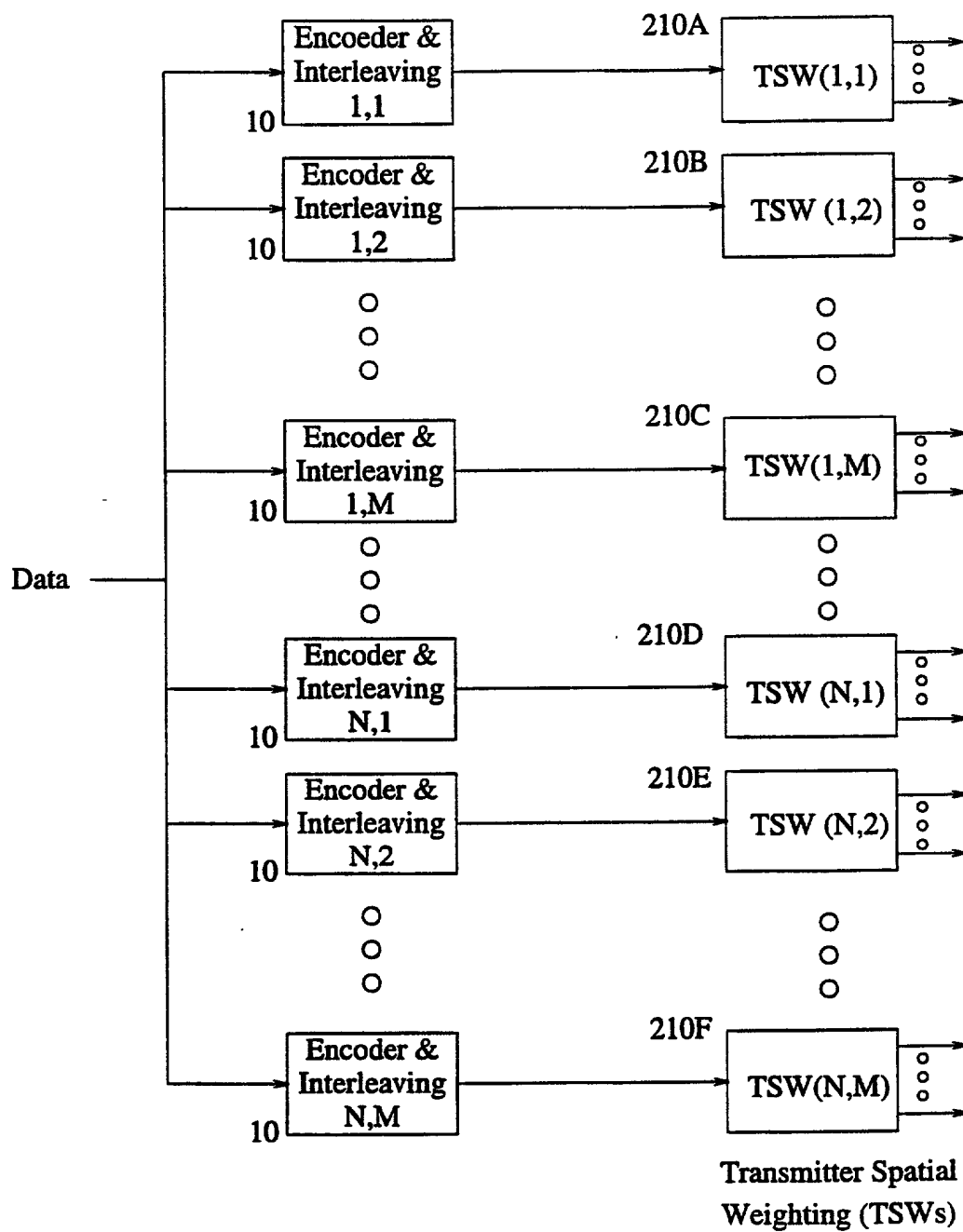
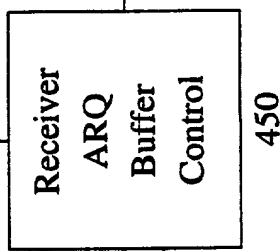
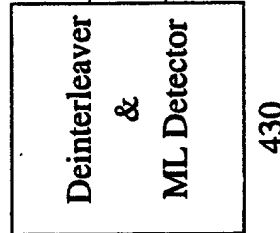
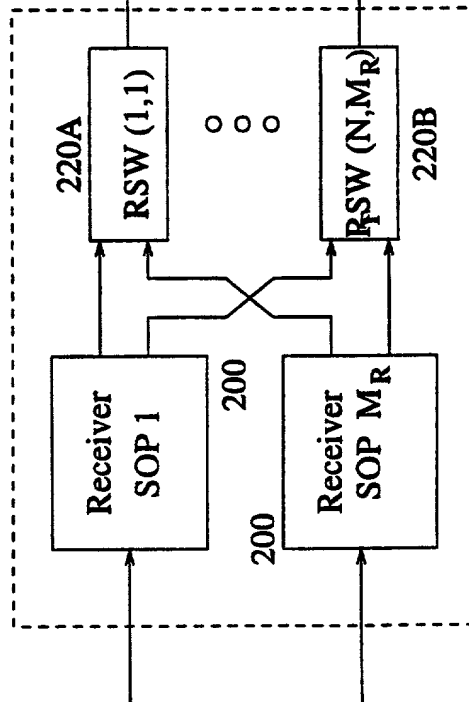
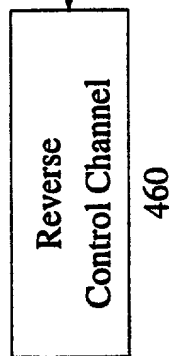
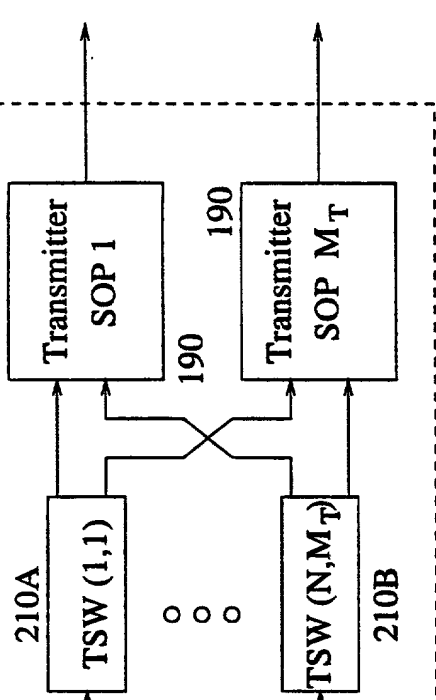
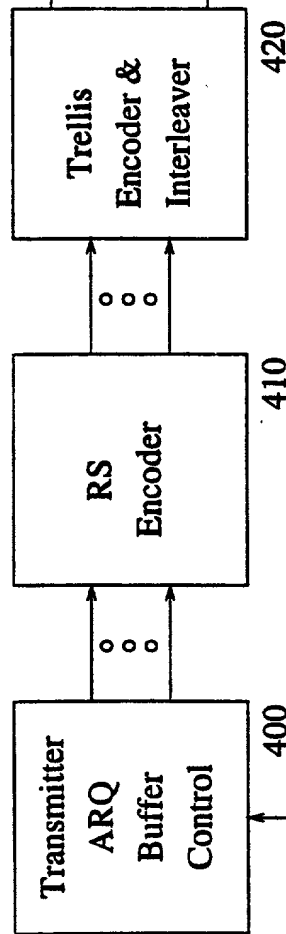


Fig. 21

Encoding and Interleaving 10



Receiver Space-Freq. Processor 140

Decoder and Deinterleaving 150

Fig. 22

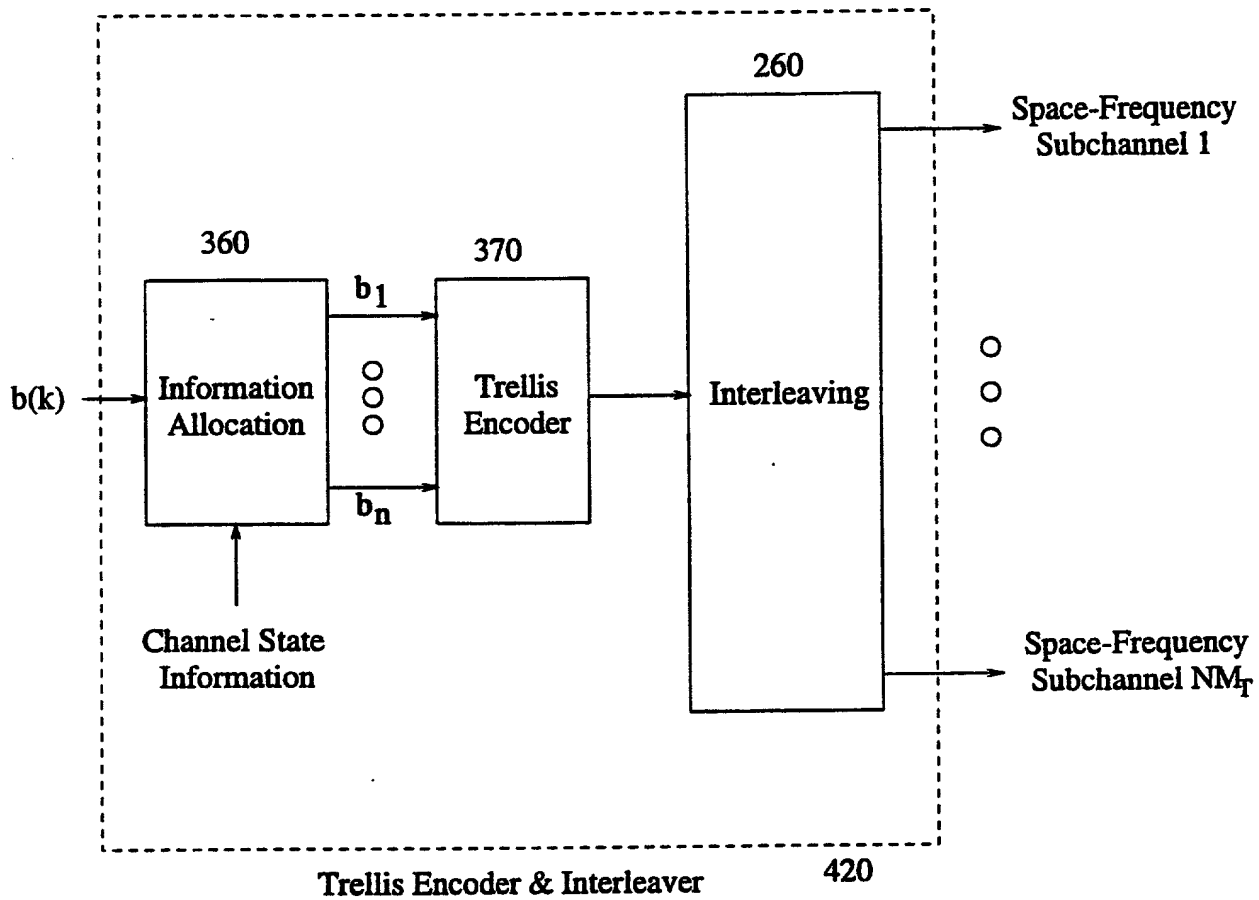


Fig. 23

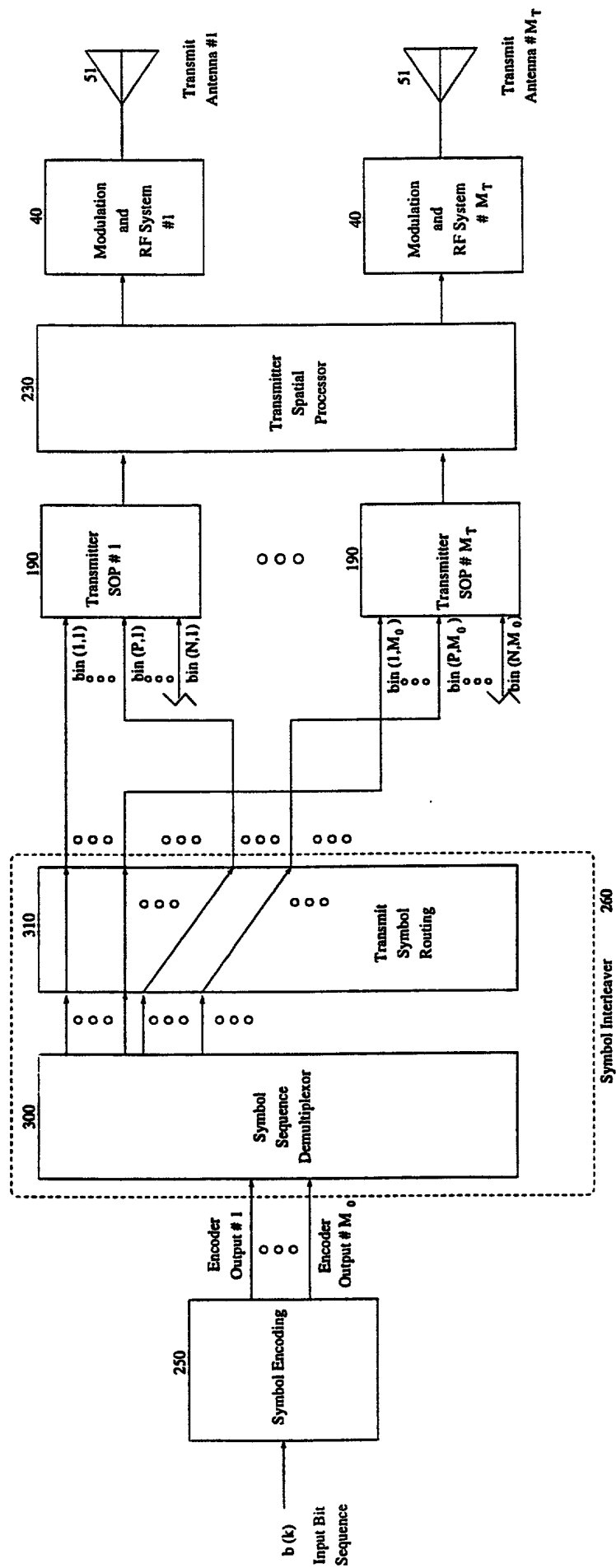


Fig. 24

111 Receive Antenna #1
 120 Demodulation and RF System #1
 240 Receiver Spatial Processor
 200 Receiver SOP #1
 130 Channel ID
 270 Symbol Deinterleaver
 320 Symbol Sequence Multiplexor
 330 Receiver Symbol Router
 280 Symbol to Bit Decoder
 Output Bit Sequence $\hat{b}(k)$

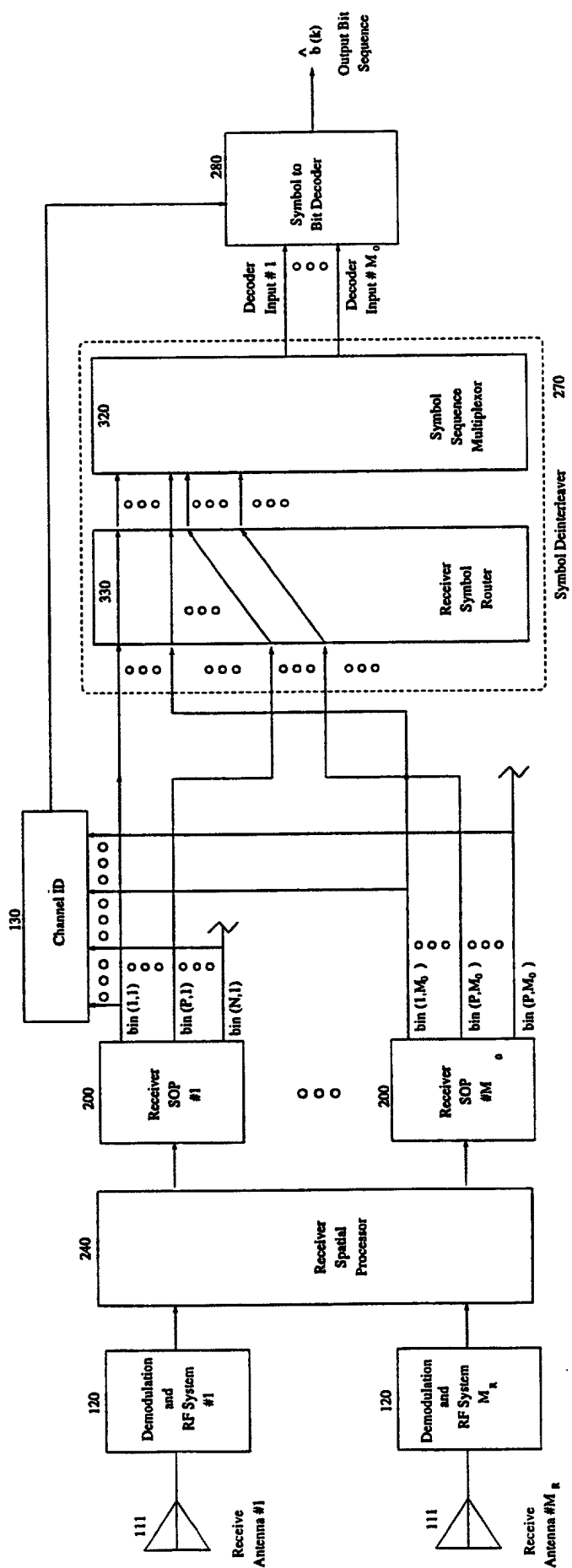


Fig. 25

FIG. 26 is a block diagram of a trellis encoder system. The system includes a trellis encoder 340, a trellis decoder 342, a trellis encoder 344, and a trellis decoder 346. The trellis encoder 340 and trellis decoder 342 are connected to a trellis encoder 344 and a trellis decoder 346. The trellis encoder 340 and trellis decoder 342 are connected to a trellis encoder 344 and a trellis decoder 346. The trellis encoder 340 and trellis decoder 342 are connected to a trellis encoder 344 and a trellis decoder 346.

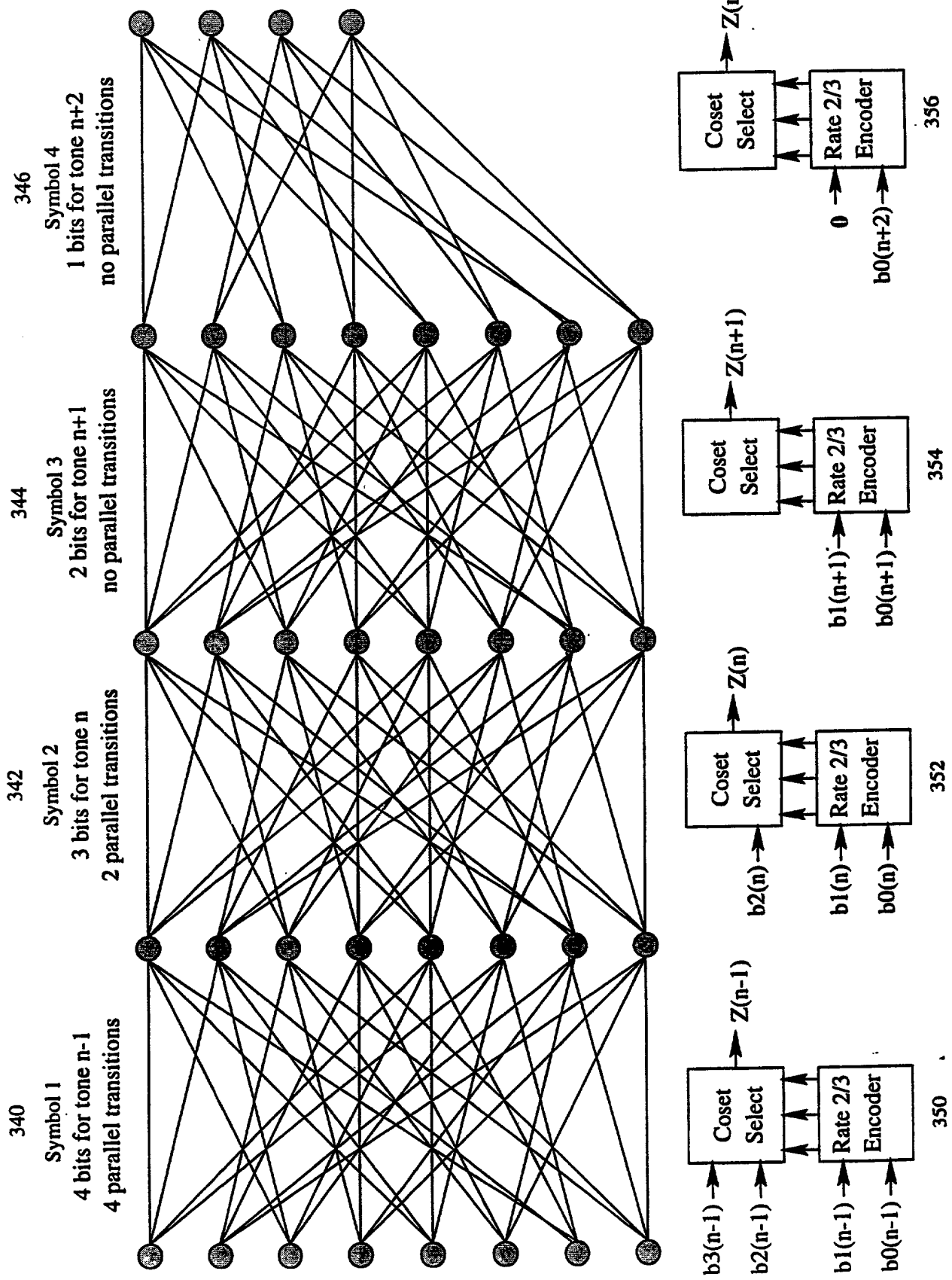


Fig. 26

DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I declare that:

My residence, post office address and citizenship are as stated below next to my name; I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural inventors are named below) of the subject matter which is claimed and for which a patent is sought on the invention entitled: **SPATIO-TEMPORAL PROCESSING FOR COMMUNICATION** the specification of which ___ is attached hereto or X was filed on August 27, 1997 as Application No. 08/921,633 and was amended on ___ (if applicable).

I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above. I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, Section 1.56. I claim foreign priority benefits under Title 35, United States Code, Section 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)

| Country | Application No. | Date of Filing | Priority Claimed Under 35 USC 119 |
|---------|-----------------|----------------|--------------------------------------|
| | | | Yes _ No _ |
| | | | Yes _ No _ |

I hereby claim the benefit under Title 35, United States Code §119(e) of any United States provisional application(s) listed below:

| Application No. | Filing Date |
|-----------------|-----------------|
| 60/025,227 | August 29, 1996 |
| 60/025,228 | August 29, 1996 |

I claim the benefit under Title 35, United States Code, Section 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, Section 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, Section 1.56 which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

| Application No. | Date of Filing | Status |
|-----------------|----------------|----------------------------------|
| | | _ Patented _ Pending _ Abandoned |
| | | _ Patented _ Pending _ Abandoned |

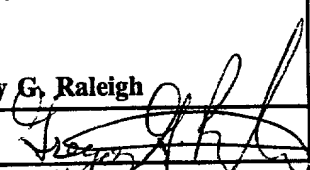

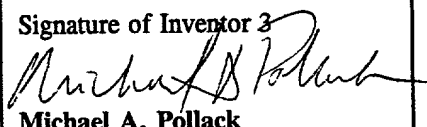
POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

Dan H. Lang, Reg. No. 38,531
Robert C. Colwell, Reg. No. 27,431

| | |
|---|--|
| Send Correspondence to: Dan H. Lang TOWNSEND and TOWNSEND and CREW LLP Two Embarcadero Center, 8th Floor San Francisco, CA 94111-3834 | Direct Telephone Calls to: (Name, Reg. No., Telephone No.) Name: Dan H. Lang Reg. No.: 38,531 Telephone: 650-326-2400 |
|---|--|

| | | | | |
|-------------------------|--|--|---|--------------------------|
| Full Name of Inventor 1 | Last Name Raleigh | First Name Gregory | Middle Name or Initial G. | |
| Residence & Citizenship | City 539 San Juan Avenue | State/Foreign Country California | Country of Citizenship U.S.A. | |
| Post Office Address | Post Office Address P.O. Box 1870 | City El Granada | State/Country California | Zip Code 94018 |
| Full Name of Inventor 2 | Last Name Jones IV | First Name Vincent | Middle Name or Initial K. | |
| Residence & Citizenship | City Redwood Shores | State/Foreign Country California | Country of Citizenship U.S.A. | |
| Post Office Address | Post Office Address 2208 Hastings Shore Lane | City Redwood Shores | State/Country California | Zip Code 94065 |
| Full Name of Inventor 3 | Last Name Pollack | First Name Michael | Middle Name or Initial A. | |
| Residence & Citizenship | City Cupertino | State/Foreign Country California | Country of Citizenship U.S.A. | |
| Post Office Address | Post Office Address 20196 Northbrook Square | City Cupertino | State/Country California | Zip Code 95014 |

I further declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

| | | |
|---|---|---|
| Signature of Inventor 1 | Signature of Inventor 2 | Signature of Inventor 3 |
|  |  |  |
| Gregory G. Raleigh | Vincent K. Jones IV | Michael A. Pollack |
| Date 3/4/98 | Date 3/4/98 | Date 3/4/98 |